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著者	ATLAS Collaboration, Hara K., Kim S.H., Okawa H., Sato K., Ukegawa F.
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# Search for the standard model Higgs boson produced in association with a vector boson and decaying into a tau pair in $pp$ collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

G. Aad *et al.*\*

(ATLAS Collaboration)

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A search for the standard model Higgs boson produced in association with a vector boson with the decay  $H \rightarrow \tau\tau$  is presented. The data correspond to  $20.3 \text{ fb}^{-1}$  of integrated luminosity from proton-proton collisions at  $\sqrt{s} = 8$  TeV recorded by the ATLAS experiment at the LHC during 2012. The data agree with the background expectation, and 95% confidence-level upper limits are placed on the cross section of this process. The observed (expected) limit, expressed in terms of the signal strength  $\mu = \sigma/\sigma_{\text{SM}}$  for  $m_H = 125$  GeV, is  $\mu < 5.6$  (3.7). The measured value of the signal strength is  $\mu = 2.3 \pm 1.6$ .

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## I. INTRODUCTION

The investigation of the origin of electroweak symmetry breaking and the experimental confirmation of the Brout-Englert-Higgs mechanism [1–6] is one of the primary goals of the physics program at the Large Hadron Collider (LHC) [7]. With the discovery of a Higgs boson with a mass of 125 GeV by the ATLAS [8] and CMS [9] Collaborations, an important milestone has been reached. To date, measurements of the couplings of the discovered particle [10–13] as well as tests of the spin-parity quantum numbers [14–16] are consistent with the predictions for the standard model (SM) Higgs boson.

In this paper, a search for the associated production of the Higgs boson with a vector boson, where the Higgs boson decays to a pair of tau leptons, is presented. This production mechanism is referred to in the following as  $VH$ , where  $V$  is either a  $W$  or  $Z$  boson. The analysis is part of a comprehensive program by the ATLAS Collaboration at the LHC to measure the Higgs boson production mechanisms, its couplings, and other characteristics. Similar studies have been performed with the  $VH$  production mechanism and subsequent decays of the Higgs boson to  $WW^*$  [17,18] and  $b\bar{b}$  [19,20] by the ATLAS and CMS Collaborations and to tau lepton pairs [21] by the CMS Collaboration. The associated production is particularly useful in the decays of the Higgs boson to tau lepton pairs when both tau leptons decay hadronically, where the trigger can be a challenge. For  $VH$  production and leptonic decays of the  $W$  or  $Z$  boson, the  $W$  and  $Z$  boson decay products satisfy the trigger requirements with high efficiency.

$VH \rightarrow W/Z\tau\tau$  production results in several different final-state signatures, which are exploited by an event categorization designed to achieve both a good signal-to-background ratio and good resolution for the reconstructed  $H \rightarrow \tau^+\tau^-$  invariant mass. Signatures consistent with  $ZH$  and  $WH$  production are exploited, where only the  $W \rightarrow \ell\nu$  and the  $Z \rightarrow \ell\ell$  decays are considered, with  $\ell = e, \mu$ . The  $H \rightarrow \tau^+\tau^-$  decay signal is reconstructed in the following two possible final states: both tau leptons decay to hadrons and a neutrino ( $\tau_{\text{had}}\tau_{\text{had}}$ ), or one tau lepton decays leptonically ( $\tau \rightarrow \ell\nu\bar{\nu}$ ) and one to hadron(s) and a neutrino ( $\tau_{\text{lep}}\tau_{\text{had}}$ ).

## II. ATLAS DETECTOR AND OBJECT RECONSTRUCTION

The ATLAS detector [22] is a multipurpose detector with a cylindrical geometry.<sup>1</sup> It consists of three subsystems: an inner detector (ID) surrounded by a thin superconducting solenoid, a calorimeter system, and a muon spectrometer in a toroidal magnetic field.

The ID tracking system reconstructs the trajectory of charged particles in the pseudorapidity range  $|\eta| < 2.5$ . It enables the accurate determination of charged-particle momentum and the position of  $b$ -hadron decay vertices. The inner detector is built from three concentric detector systems surrounded by a solenoid providing a uniform axial 2 T field. The three detector systems are the pixel

\*Full author list given at the end of the article.

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<sup>1</sup>The ATLAS experiment uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the  $z$  axis along the beam direction. The  $x$  axis points from the IP to the center of the LHC ring, and the  $y$  axis points upward. Cylindrical coordinates  $(r, \phi)$  are used in the transverse  $(x, y)$  plane,  $\phi$  being the azimuthal angle around the beam direction. The pseudorapidity is defined in terms of the polar angle  $\theta$  as  $\eta = -\ln \tan(\theta/2)$ . The angular distance  $\Delta R$  in the  $\eta$ - $\phi$  space is defined as  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ .

detector, the silicon microstrip detector, and the transition radiation tracker.

The ID tracking system is surrounded by high-granularity lead/liquid-argon (LAr) sampling electromagnetic calorimeters covering the pseudorapidity range  $|\eta| < 3.2$ . A steel/scintillator tile calorimeter provides hadronic energy measurements in the pseudorapidity region  $|\eta| < 1.7$ . In the regions  $1.5 < |\eta| < 4.9$ , the hadronic energy measurements are provided by two end-cap LAr calorimeters using copper or tungsten as absorbers.

The muon spectrometer surrounds the calorimeters. It extends tracking beyond the calorimeter, which enables the identification of muons and a precision measurement of their properties. It consists of three large superconducting eight-coil toroids, a system of tracking chambers, and detectors for triggering. Muon tracking is performed with monitored drift tubes covering  $|\eta| < 2.7$  and cathode strip chambers covering  $|\eta| > 2.0$ , while trigger information is collected in the resistive plate chambers in the barrel ( $|\eta| < 1.05$ ) and thin-gap chambers in the end-cap regions ( $1.05 < |\eta| < 2.4$ ).

A three-level trigger system [23] is used to select events. A hardware-based level-1 trigger uses a subset of detector information to reduce the event rate to a value of 75 kHz or less. The rate of accepted events is then reduced to about 400 Hz by two software-based trigger levels, level-2 and the event filter.

A primary vertex is identified for each event. The reconstructed primary vertex position [24] is required to be consistent with the interaction region and to have at least five associated tracks with transverse momentum  $p_T > 400$  MeV; when more than one such vertex is found, the vertex with the largest summed  $p_T^2$  of the associated tracks is chosen.

The tau leptons that decay to hadron(s) and a neutrino, or  $\tau_{\text{had}}$ , are reconstructed using clusters of energy deposited in the electromagnetic and hadronic calorimeters that are matched to tracks in the inner detector. The identification algorithm separates  $\tau_{\text{had}}$  candidates from jets using  $\tau_{\text{had}}$  decay characteristics, namely the number of tracks, the collimation of energy deposits in the calorimeter, and the mass of the  $\tau_{\text{had}}$  candidate. The analysis presented here utilizes  $\tau_{\text{had}}$  candidates seeded by an anti- $k_t$  jet algorithm with radius parameter  $R = 0.4$  [25,26], with jet  $p_T > 20$  GeV and  $|\eta| < 2.5$ . The  $\tau_{\text{had}}$  candidates must have only one or three associated tracks in a cone of size  $\Delta R = 0.2$ . All  $\tau_{\text{had}}$  candidates are required to have charge  $\pm 1$ , calculated by summing the charges of the associated tracks. The  $\tau_{\text{had}}$  decay products are identified by a boosted decision tree (BDT) [27], which returns a number between zero and one depending on how jetlike or tau-like the reconstructed object is. The BDT selects taus with a 55%–60% efficiency (medium  $\tau_{\text{had}}$  identification) depending on the  $\tau_{\text{had}}$  number of tracks,  $\eta$ , and  $p_T$ . Dedicated algorithms reject candidates originating from electrons and muons.

Electron candidates are reconstructed from clusters of energy deposited in the electromagnetic calorimeter that are matched to tracks in the inner detector. They are required to be within the pseudorapidity range  $|\eta| < 2.47$  and must have shower shape and track measurements that fulfill the set of medium quality criteria [28], which provides electron identification efficiencies of 80%–90% depending on the transverse energy  $E_T$ , and  $\eta$  of the electron candidate. Electrons are considered isolated based on tracking and calorimeter information. The calorimeter isolation requires the sum of the transverse energy in the calorimeter in a cone of size  $\Delta R = 0.4$  around the electron cluster, divided by the  $E_T$  of the electron cluster, to be less than 8% of the electron cluster  $E_T$ . The track-based isolation requires the sum of the transverse momenta of tracks within a cone of  $\Delta R = 0.2$  around the electron, divided by the  $E_T$  of the electron cluster, to be less than 8% of the electron cluster  $E_T$ .

Muon candidates are reconstructed from tracks in the inner detector matched to tracks in the muon spectrometer. A requirement on the distance between the primary vertex and the point where the muon candidate track crosses the beam line reduces the background from cosmic rays and beam-induced backgrounds. Muon candidates are required to be within the pseudorapidity range  $|\eta| < 2.5$  and must satisfy a set of quality criteria [29], which provides muon identification efficiencies above 95%. Muons are considered isolated based on tracking and calorimeter information with similar requirements as are used for electrons, with the muon track  $p_T$  in place of the electron cluster  $E_T$ .

Jets are reconstructed from clusters in the calorimeter using the anti- $k_t$   $R = 0.4$  jet algorithm. Corrections for the detector response are applied [30,31]. To reduce the contamination of jets by additional interactions in the same or neighboring bunch crossings (pileup), tracks originating from the primary vertex must contribute at least 50% of the total scalar sum of track  $p_T$  within the jets. This requirement is only applied to jets with  $p_T < 50$  GeV and  $|\eta| < 2.4$ .

A  $b$ -tagging algorithm that relies on tracking information and  $b$ -hadron characteristics, such as the presence of a decay that can be separated from the primary vertex, is used to identify  $b$ -jets [32]. The operating point for  $b$ -tagging chosen for this analysis has a 70% efficiency for  $b$ -jets in simulated  $t\bar{t}$  events with a corresponding misidentification probability for light-quark jets of 1%.

Missing transverse momentum, with magnitude  $E_T^{\text{miss}}$ , is reconstructed using the energy deposits in calorimeter cells calibrated according to the reconstructed physics objects ( $e$ ,  $\mu$ ,  $\tau_{\text{had}}$ , jets) with which they are associated. Energy deposits not associated with a physics object tend to have low  $p_T$  and are scaled by a dedicated algorithm tuned to improve the resolution in high-pileup conditions [33].

TABLE I. Monte Carlo generators used to model the signal and the background processes at  $\sqrt{s} = 8$  TeV. The cross sections times branching fractions ( $\sigma \times \mathcal{B}$ ) used for the normalization of some processes are included in the last column together with the perturbative order of the QCD calculation. For the signal process only the  $H \rightarrow \tau\tau$  SM branching fraction is included. For the  $W$  and  $Z/\gamma^*$  background processes the branching ratios for leptonic decays ( $l = e, \mu, \tau$ ) are included. For all other background processes, inclusive cross sections are quoted (marked with a  $\dagger$ ).

Signal (Higgs boson mass $m_H = 125$ GeV)	MC generator	$\sigma \times \mathcal{B}$ (pb) at $\sqrt{s} = 8$ TeV		
$WH, H \rightarrow \tau\tau$	PYTHIA8	0.0445	NNLO	[34,35]
$ZH, H \rightarrow \tau\tau$	PYTHIA8	0.0262	NNLO	[34,35]
Background				
$W(\rightarrow l\nu), (l = e, \mu, \tau)$	ALPGEN [36]+PYTHIA8	36800	NNLO	[37,38]
$Z/\gamma^*(\rightarrow ll),$ $60 \text{ GeV} < m_{ll} < 2 \text{ TeV}$	ALPGEN+PYTHIA8	3910	NNLO	[37,38]
$Z/\gamma^*(\rightarrow ll),$ $10 \text{ GeV} < m_{ll} < 60 \text{ GeV}$	ALPGEN+HERWIG [39]	13000	NNLO	[37,38]
$t\bar{t}$	MC@NLO [40] + JIMMY[41]	238 $^\dagger$	NLO	[40]
$q\bar{q} \rightarrow WW$	ALPGEN+HERWIG	54 $^\dagger$	NLO	[42]
$gg \rightarrow WW$	GG2WW[43]+HERWIG	1.4 $^\dagger$	NLO	[43]
$WZ, ZZ$	HERWIG	30 $^\dagger$	NLO	[42]

### III. DATA AND SIMULATION SAMPLES

The analysis uses those data collected when the detector systems were certified as functioning properly. The resulting data sample corresponds to an integrated luminosity of  $20.3 \text{ fb}^{-1}$  of  $pp$  collisions at  $\sqrt{s} = 8$  TeV. Samples of signal and background events are simulated using a number of Monte Carlo (MC) generators, listed in Table I. The cross-section values to which the simulation is normalized and the perturbative order in quantum chromodynamics (QCD) for each calculation are also provided. For the signal samples, the central value of the factorization scale equals the sum of the Higgs boson mass and the vector boson mass.

The generated events are combined with minimum-bias events simulated using the AU2 [44] parameter tuning of PYTHIA8 [45] to take into account multiple interactions. All simulated events undergo full simulation of the ATLAS detector response [46] using the GEANT4[47] simulation program before being processed through the same reconstruction algorithms as the data. The signal samples use the CTEQ6L1 [48] PDF set.

### IV. EVENT CATEGORIZATION AND SELECTION

A characteristic of  $VH$  production is the presence of a  $W$  or  $Z$  boson in each signal event. The analysis categories are optimized to exploit the leptonic decays of the vector bosons that provide a candidate for the electron or muon triggers and to reduce the backgrounds from multijet processes. The presence of additional leptonic and/or hadronic tau decays from the Higgs boson allows for the event selection to include a requirement on three or four objects, depending on the channel, to define the final state.

The single-lepton and dilepton triggers used to select the events in this analysis are listed in Table II. The  $p_T$  requirements on the particle candidates in the analysis are 2 GeV higher than the trigger thresholds, to ensure that the trigger is maximally efficient.

The four analysis event categories are determined by the type of associated vector boson and the topology of the  $H \rightarrow \tau\tau$  decay. These are summarized in Table III and described below.

- (i) The  $W \rightarrow \mu\nu/e\nu, H \rightarrow \tau_{\text{lep}}\tau_{\text{had}}$  channel: These events are required to have one isolated electron, one isolated muon, and one  $\tau_{\text{had}}$  candidate. The electron and muon candidates are required to have an electric charge of the same sign to reduce the backgrounds from  $Z/\gamma^* \rightarrow \tau\tau + \text{jets}$  events,  $WW$  events, and  $t\bar{t}$  events where both  $W$  bosons decay leptonically. The electron or muon candidate with the higher  $p_T$  is assumed to arise from the  $W$  boson decay, which is correct 75% of the time in the MC simulation. The  $\tau_{\text{had}}$  candidate is required to have  $p_T > 25$  GeV and to have opposite electric charge

TABLE II. Summary of the triggers used to select events for the various channels. The transverse momentum thresholds applied at trigger level are listed.

Trigger	Trigger threshold(s) (GeV)
Single electron	$p_T^e > 24$
Single muon	$p_T^\mu > 24$
Combined electron and muon	$p_T^e > 12 \ p_T^\mu > 8$
Symmetric dielectron	$p_T^{e_1} > 12 \ p_T^{e_2} > 12$
Asymmetric dielectron	$p_T^{e_1} > 24 \ p_T^{e_2} > 7$
Symmetric dimuon	$p_T^{\mu_1} > 13 \ p_T^{\mu_2} > 13$
Asymmetric dimuon	$p_T^{\mu_1} > 18 \ p_T^{\mu_2} > 8$



TABLE III. Summary of the selection criteria for each of the four analysis channels.

Channel	Selections
$W \rightarrow \mu\nu/e\nu$ , $H \rightarrow \tau_{\text{lep}}\tau_{\text{had}}$	Exactly one isolated electron and one isolated muon Exactly one $\tau_{\text{had}}$ passing medium BDT ID $p_T(\tau_{\text{had}}) > 25$ GeV Same-charge $e$ and $\mu$ , oppositely charged $\tau_{\text{had}}$ Events containing $b$ -tagged jets with $p_T > 30$ GeV are vetoed $ p_T(\tau_{\text{had}})  +  p_T(\mu)  +  p_T(e)  > 80$ GeV $\Delta R(\tau_{\text{had}}, \tau_{\text{lep}}) < 3.2$
$W \rightarrow \mu\nu/e\nu$ , $H \rightarrow \tau_{\text{had}}\tau_{\text{had}}$	Exactly one isolated electron or one isolated muon Exactly two $\tau_{\text{had}}$ passing medium BDT ID of opposite charge $p_T(\tau_{\text{had}}) > 20$ GeV $ p_T(\tau_{\text{had}}^1)  +  p_T(\tau_{\text{had}}^2)  > 100$ GeV $m_T(\ell, E_T^{\text{miss}}) > 20$ GeV $0.8 < \Delta R(\tau_{\text{had}}^1, \tau_{\text{had}}^2) < 2.8$ Events containing $b$ -tagged jets with $p_T > 30$ GeV are vetoed
$Z \rightarrow \mu\mu/ee$ , $H \rightarrow \tau_{\text{lep}}\tau_{\text{had}}$	Exactly three electrons or muons, One opposite-charge and same-flavor lepton pair with invariant mass $80 < m_{\ell\ell} < 100$ GeV Exactly one $\tau_{\text{had}}$ passing medium BDT ID, with opposite charge to the lepton assigned to the Higgs boson $p_T(\tau_{\text{had}}) > 20$ GeV $ p_T(\tau_{\text{had}})  +  p_T(\tau_{\text{lep}})  > 60$ GeV
$Z \rightarrow \mu\mu/ee$ , $H \rightarrow \tau_{\text{had}}\tau_{\text{had}}$	Exactly two electrons or two muons of opposite charge Exactly two $\tau_{\text{had}}$ passing medium BDT ID of opposite charge $p_T(\tau_{\text{had}}) > 20$ GeV $60 < m_{\ell\ell} < 120$ GeV $ p_T(\tau_{\text{had}}^1)  +  p_T(\tau_{\text{had}}^2)  > 88$ GeV

to the leptons. Events containing  $b$ -tagged jets with  $p_T > 30$  GeV are vetoed to further reduce the background from  $t\bar{t}$  events. The scalar sum of the  $p_T$  of the electron, muon, and  $\tau_{\text{had}}$  candidates must be greater than 80 GeV to reduce the backgrounds from multijet and  $Z/\gamma^* + \text{jets}$  events. To reduce backgrounds from quark- or gluon-initiated jets misidentified as  $\tau_{\text{had}}$  when these jets are produced back to back, the angle between the  $\tau_{\text{had}}$  and  $\tau_{\text{lep}}$  candidates associated with the Higgs boson is required to satisfy  $\Delta R(\tau_{\text{had}}, \tau_{\text{lep}}) < 3.2$ .

- (ii) The  $W \rightarrow \mu\nu/e\nu, H \rightarrow \tau_{\text{had}}\tau_{\text{had}}$  channel: These events are required to have one isolated electron or muon candidate and two  $\tau_{\text{had}}$  candidates. The two

$\tau_{\text{had}}$  candidates are required to have  $p_T > 20$  GeV and to have opposite charge. The lepton is assumed to come from the  $W$  boson. Events containing  $b$ -tagged jets with  $p_T > 30$  GeV are vetoed to reduce the background from  $t\bar{t}$  events. The scalar sum of the  $p_T$  of the lepton and two  $\tau_{\text{had}}$  candidates must be greater than 100 GeV in order to reduce the background from multijet events. The transverse mass<sup>2</sup> of the lepton and  $E_T^{\text{miss}}$  must be greater than 20 GeV. To reduce the background from events with jets misidentified as  $\tau_{\text{had}}$  candidates,  $0.8 < \Delta R(\tau_{\text{had}}^1, \tau_{\text{had}}^2) < 2.8$  is required, which results in a reduction of the background from misidentified jets by almost a factor of 2 while losing less than a third of the signal events.

- (iii) The  $Z \rightarrow \mu\mu/ee, H \rightarrow \tau_{\text{lep}}\tau_{\text{had}}$  channel: Events containing one  $\tau_{\text{had}}$  candidate and three light lepton candidates are in this category. The two light lepton candidates with invariant mass closest to 91 GeV, opposite electric charge, and the same flavor are assumed to be the  $Z$  boson decay products. The invariant mass of the leptons assumed to come from the  $Z$  must be between 80 and 100 GeV. The remaining light lepton and the  $\tau_{\text{had}}$  candidate are assumed to originate from the Higgs boson decay. They are thus required to have opposite charge and the scalar sum of their  $p_T$  values must be greater than 60 GeV.
- (iv) The  $Z \rightarrow \mu\mu/ee, H \rightarrow \tau_{\text{had}}\tau_{\text{had}}$  channel: Signal candidates are selected by requiring exactly two electron (muon) candidates and two  $\tau_{\text{had}}$  candidates. The two light leptons are assigned to the  $Z$  boson decay, are required to have the same flavor, and are required to have opposite electric charge. The invariant mass of the two lepton candidates assigned to the  $Z$  boson must be between 60 and 120 GeV. The two  $\tau_{\text{had}}$  candidates are assumed to originate from the Higgs boson decay and are required to have opposite electric charge. A minimum requirement of 88 GeV is placed on the scalar sum of the transverse momenta of the  $\tau_{\text{had}}$  pair to reduce the  $Z/\gamma^* + \text{jets}$  background.

After all the analysis selection criteria are applied, the number of events migrating from other Higgs boson channels, in particular from  $VH$  production where the Higgs boson decays into  $WW$ , is found to be negligible. This analysis selection has an acceptance of 1.9% for the combined  $WH$  channels, where the denominator requires a light lepton from the  $W$  boson decay ( $W \rightarrow \mu\nu/e\nu/\tau_{e/\mu}\nu$ ) and for the Higgs boson to decay through the considered tau decay chains ( $H \rightarrow \tau_{\text{lep}}\tau_{\text{had}}$  or

<sup>2</sup>The transverse mass is  $m_T = \sqrt{2p_T^\ell E_T^{\text{miss}}(1 - \cos\Delta\phi)}$ , where  $\Delta\phi$  is the azimuthal separation between the directions of the lepton and the missing transverse momentum.

TABLE IV. The loosened signal selection and the list of validation regions used to validate the fake-factor method are given for each of the four analysis channels. Missing mass calculator (MMC) and  $M_{2T}$  are mass reconstruction techniques defined in Sec. VI.

Channel	Loosened signal selection	Validation regions
$W \rightarrow \mu\nu/e\nu, H \rightarrow \tau_{\text{lep}}\tau_{\text{had}}$	One isolated electron One isolated muon $p_T(\tau_{\text{had}}) > 25$ GeV	$Z \rightarrow \tau\tau$ : $Z$ mass selection (60–120 GeV) $t\bar{t}$ : require $b$ -tagged jet
$W \rightarrow \mu\nu/e\nu, H \rightarrow \tau_{\text{had}}\tau_{\text{had}}$	One isolated electron or muon Two (opposite charge) $\tau_{\text{had}}$ candidates	$Z \rightarrow \tau\tau$ : $Z$ mass selection ( $> 60$ GeV) $t\bar{t}$ : require $b$ -tagged jet $W$ + jets: $m_T(\ell, E_T^{\text{miss}}) > 60$ GeV Same-sign $\tau_{\text{had}}$ candidates Mass sideband: $M_{2T} < 60$ GeV or $M_{2T} > 120$ GeV
$Z \rightarrow \mu\mu/ee, H \rightarrow \tau_{\text{lep}}\tau_{\text{had}}$	Three isolated electrons or muons Opposite-charge, same-flavor lepton pair $\tau_{\text{had}}$ with opposite charge to the unpaired lepton	Same-sign $\tau_{\text{lep}}, \tau_{\text{had}}$ candidates Mass sideband: $M_{\text{MMC}} < 80$ GeV or $M_{\text{MMC}} > 120$ GeV
$Z \rightarrow \mu\mu/ee, H \rightarrow \tau_{\text{had}}\tau_{\text{had}}$	Two opposite-charge, same-flavor leptons Two opposite-charge $\tau_{\text{had}}$ candidates	Same-sign $\tau_{\text{had}}$ candidates Mass sideband: $M_{\text{MMC}} < 80$ GeV or $M_{\text{MMC}} > 120$ GeV

$H \rightarrow \tau_{\text{had}}\tau_{\text{had}}$ ), and the numerator includes all analysis cuts. The acceptance for the combined  $ZH$  channels is 5.3%, where the denominator requires a light lepton pair from the  $Z$  boson decay ( $Z \rightarrow \mu\mu/ee/\tau\tau_{\mu\mu/ee}$ ) and for the Higgs boson to decay through the considered tau decay chains ( $H \rightarrow \tau_{\text{lep}}\tau_{\text{had}}$  or  $H \rightarrow \tau_{\text{had}}\tau_{\text{had}}$ ), and the numerator includes all analysis cuts.

## V. BACKGROUND ESTIMATION

The number of expected background events and the associated kinematic distributions are derived using data-driven methods as well as simulation. There are two classes of backgrounds for this analysis: processes in which all three or four final-state lepton and  $\tau_{\text{had}}$  candidates are actually produced, and those in which some lepton or  $\tau_{\text{had}}$  candidates are actually misidentified jets. Jets are most likely to be misidentified as  $\tau_{\text{had}}$  objects, although the rate at which jets mimic electrons is, in some instances, not negligible.

Backgrounds containing real electrons, muons, and  $\tau_{\text{had}}$  leptons primarily arise from diboson,  $Z \rightarrow \tau\tau$ , and  $t\bar{t}$  events. These backgrounds are determined from Monte Carlo simulation. The background arising from jets misidentified as electron or  $\tau_{\text{had}}$  candidates is estimated using a data-driven method, the so-called fake-factor method. The  $\tau_{\text{had}}$  fake factor is defined as the ratio of the number of  $\tau_{\text{had}}$  candidates identified with medium  $\tau_{\text{had}}$  criteria to the number satisfying the loosened but not the medium identification criteria. The electron fake factor is defined as the number of electrons satisfying the identification criteria divided by the number of those that do not. The fake-factor measurements are described below. For the  $W \rightarrow \mu\nu/e\nu, H \rightarrow \tau_{\text{lep}}\tau_{\text{had}}$  channel both the  $\tau_{\text{had}}$  and

electron fake factors are used, while for the other three channels the  $\tau_{\text{had}}$  fake-factor method alone performs well enough for modeling the background from misidentified jets. The background from misidentified jets is the dominant background, or comparable to the background from diboson production, in all channels of the analysis.

Since the fake rates are sensitive to the underlying physics of the event, the fake factors are measured in a region with similar kinematics and composition of misidentified objects to the signal region. Applying the analysis selection to MC simulation reveals that  $Z/\gamma^* + \text{jets}$  events are the primary source of the background from misidentified jets in the analysis. The rate of jets mimicking the  $\tau_{\text{had}}$  selection is therefore measured using a tag-and-probe method from jets in well-reconstructed  $Z/\gamma^* \rightarrow \mu\mu + \text{jets}$  events. The tag here is the dimuon system and the probe is the additional jet(s) that may be suitably tau-like (pass medium  $\tau_{\text{had}}$  identification) or suitably jet-like (pass a loosened  $\tau_{\text{had}}$  identification but fail the medium one). The fake factor is measured as a function of the jet  $p_T$ ,  $\eta$ , and number of associated tracks. The fake rate for electrons is calculated separately, using well-reconstructed  $Z \rightarrow \mu\mu$  events containing additional jets or photons, using the same procedure as described above.

To estimate the background from misidentified jets for the  $WH$  and  $ZH$  signal regions, these factors are then applied to the event combinations that have all selections the same as the signal selection with the exception that at least one  $\tau_{\text{had}}$  candidate has passed the loosened but failed the medium  $\tau_{\text{had}}$  identification. For the  $W \rightarrow \mu\nu/e\nu, H \rightarrow \tau_{\text{lep}}\tau_{\text{had}}$  channel, a contribution from jets misidentified as the electron candidate is also taken into

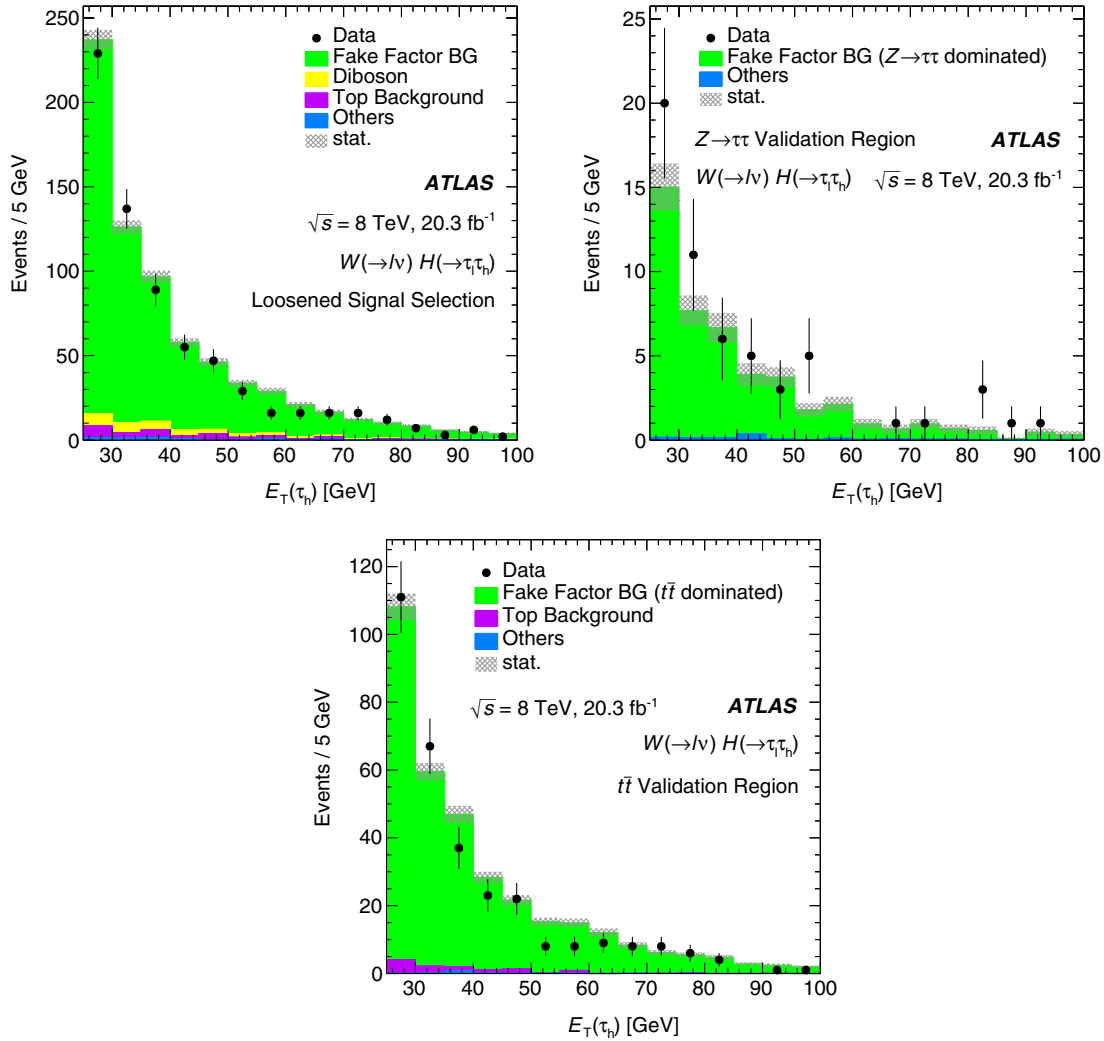


FIG. 1. Distributions of the transverse energy of the  $\tau_{\text{had}}$  candidate, as validation for the fake factor method for the  $W \rightarrow \mu\nu/e\nu, H \rightarrow \tau_{\text{lep}}\tau_{\text{had}}$  channel. The category labeled “Fake Factor BG” consists of events where at least one  $\tau_{\text{had}}$  or electron candidate does not result from a simulated  $\tau_{\text{had}}$  or electron.

account using objects that have failed electron identification. Since many background events contain multiple jets that could potentially pass the  $\tau_{\text{had}}$  or electron identification, more than one possible combination of passing and failing objects is allowed to contribute per event. In these cases, the multiple copies of the events contribute with the various weights calculated for each combination of objects considered.

The fake-factor method is validated independently in each of the four analysis channels. In each case a comparison between the data and the background prediction is made with a loosened signal selection, which provides a test of the method with a large number of events in a data set that is dominated by the background from misidentified jets. In addition, a series of orthogonal regions are formed to validate the method for each of the analysis channels. The definition of the loosened signal selection and validation regions are given for each channel in Table IV.

Example distributions of the  $p_T$  of  $\tau_{\text{had}}$  candidates for the loosened signal selection and validation regions are shown in Fig. 1 for the  $W \rightarrow \mu\nu/e\nu, H \rightarrow \tau_{\text{lep}}\tau_{\text{had}}$  channel. MC simulation studies show that this  $Z \rightarrow \tau\tau$  validation region is dominated by  $Z \rightarrow \tau\tau$  events where an additional jet in the event is misidentified as a  $\tau_{\text{had}}$  candidate. Likewise, MC simulation studies show that this  $t\bar{t}$  validation region is dominated by  $t\bar{t}$  events where at least one  $W$  boson decays leptonically and where a jet is misidentified as a  $\tau_{\text{had}}$  candidate. The number of expected signal events and estimated total number of background events for each channel in the signal region are given in Table V.

## VI. MASS RECONSTRUCTION

The result is extracted using a fit to the reconstructed invariant mass or transverse mass spectrum of the  $\tau_{\text{lep}}\tau_{\text{had}}$  or  $\tau_{\text{had}}\tau_{\text{had}}$  pair. The mass is reconstructed using one of

TABLE V. The yields for the observed and expected background and signal for a 125 GeV Higgs boson in the signal region for each individual channel. The “Other” column consists primarily of background from  $t\bar{t}$  events. The uncertainties quoted are statistical only.

Channel	Observed	Signal	$\Sigma$ Background	Fake factor	Diboson	Other
$W \rightarrow \mu\nu/e\nu, H \rightarrow \tau_{\text{lep}}\tau_{\text{had}}$	35	$1.95 \pm 0.05$	$32.4 \pm 1.9$	$13.1 \pm 1.3$	$13.54 \pm 0.35$	$5.7 \pm 1.4$
$W \rightarrow \mu\nu/e\nu, H \rightarrow \tau_{\text{had}}\tau_{\text{had}}$	33	$1.84 \pm 0.04$	$35.5 \pm 2.7$	$28.1 \pm 2.4$	$7.4 \pm 1.2$	...
$Z \rightarrow \mu\mu/ee, H \rightarrow \tau_{\text{lep}}\tau_{\text{had}}$	24	$1.14 \pm 0.03$	$24.6 \pm 1.5$	$17.1 \pm 1.5$	$7.28 \pm 0.16$	$0.20 \pm 0.01$
$Z \rightarrow \mu\mu/ee, H \rightarrow \tau_{\text{had}}\tau_{\text{had}}$	7	$0.64 \pm 0.02$	$6.8 \pm 1.2$	$4.7 \pm 1.2$	$2.09 \pm 0.09$	$0.012 \pm 0.003$

two methods, depending on the signal category. The Higgs boson mass in  $ZH$  events is calculated using the missing mass calculator (MMC) method described in Ref. [49]. This method takes the  $x$  and  $y$  components of the event missing transverse momentum as an input as well as the visible mass of the  $\tau_{\text{lep}}\text{--}\tau_{\text{had}}$  or  $\tau_{\text{had}}\text{--}\tau_{\text{had}}$  pair. Because the neutrinos from the tau decays have unknown  $x$ ,  $y$  and  $z$  components and there are multiple neutrinos (two for the

$\tau_{\text{had}}\text{--}\tau_{\text{had}}$  case and three for the  $\tau_{\text{lep}}\text{--}\tau_{\text{had}}$  case), the system is underconstrained. A scan is therefore performed over possible momenta for the neutrinos, and a most-likely di- $\tau$  mass is found.

In the  $WH$  category, the presence of an additional neutrino from the  $W$  decay makes the MMC mass reconstruction not optimal. In this case the  $M_{2T}$  variable defined in Ref. [50] is used, which calculates an

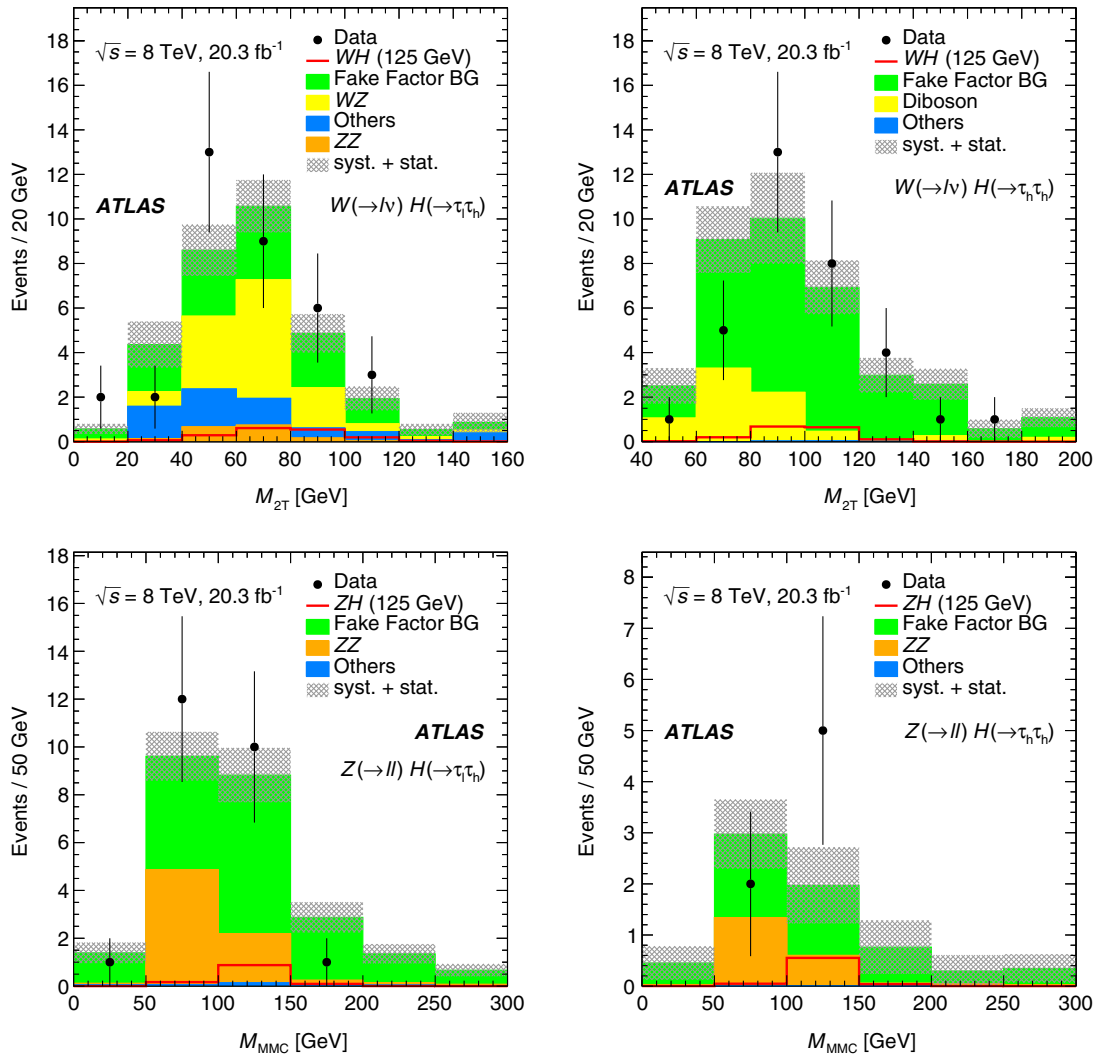


FIG. 2. Mass distributions used to determine the strength of signal in each channel. Upper left:  $M_{2T}$  distribution for the  $WH \rightarrow \tau_{\text{lep}}\tau_{\text{had}}$  channel. Upper right:  $M_{2T}$  distribution for the  $WH \rightarrow \tau_{\text{had}}\tau_{\text{had}}$  channel. Lower left:  $M_{\text{MMC}}$  distribution for the  $ZH \rightarrow \tau_{\text{lep}}\tau_{\text{had}}$  channel. Lower right:  $M_{\text{MMC}}$  distribution for the  $ZH \rightarrow \tau_{\text{had}}\tau_{\text{had}}$  channel.



event-by-event lower bound (within the detector resolution) of the transverse mass of the  $\tau_{\text{had}}\text{--}\tau_{\text{had}}$  or  $\tau_{\text{lep}}\text{--}\tau_{\text{had}}$  pair by performing a minimization over the allowed phase space of possible momenta of assumed neutrinos in the event. In the general case described in Ref. [50] the only constraint on the phase space is that the sum of the transverse momenta of all neutrinos equals the observed  $E_{\text{T}}^{\text{miss}}$ . For this analysis, the additional constraint that the invariant mass of the lepton and neutrino assigned to the  $W$  boson be equal to, or as close as possible to, the mass of the  $W$  boson is imposed. The mass distributions after all the selection criteria are applied are shown in Fig. 2.

## VII. SYSTEMATIC UNCERTAINTIES

The numbers of expected signal and background events, and the distributions of the discriminating variables  $M_{\text{MMC}}$  and  $M_{2\text{T}}$ , are affected by systematic uncertainties. These uncertainties are discussed below and are grouped into three categories: experimental uncertainties, background modeling uncertainties, and theoretical uncertainties. For all uncertainties, the effects on both the total signal and

TABLE VI. Impact of systematic uncertainties on the expected yields of the signal and/or relevant background(s) as well as the impact on the signal strength  $\mu$ . The experimental uncertainties affect the signal prediction and all backgrounds that are determined with MC simulation. The background model uncertainties affect the prediction of the backgrounds from fake-factor methods. The theoretical uncertainties affect the signal prediction. Where ranges are given they indicate the variation of the impact on different channels or differences between one-track and multitrack  $\tau_{\text{had}}$  candidates. All values are given before the global fit.

Source	Impact on event yield (%)	Impact on $\mu$
Experimental		
Luminosity	$\pm 2.8$	$\pm 0.30$
Tau identification	$\pm 2\text{--}6$	$\pm 0.41$
Lepton identification and trigger	$\pm 1\text{--}1.8$	$\pm 0.15$
$b$ -tagging	$\pm 2$	$\pm 0.16$
$\tau$ energy scale	$\pm 0\text{--}2.9$	$\pm 0.57$
Jet energy scale and resolution	$\pm 4$	$\dots$
$E_{\text{T}}^{\text{miss}}$ soft scale and resolution	$\pm 0.1\text{--}0.5$	$\dots$
Background model		
Modeling of BG from misidentified jets	$\pm 15\text{--}38$	$\pm 0.72$
Theoretical		
Higher-order QCD corrections	$\pm 2\text{--}8$	$\pm 0.26$
Underlying event/parton shower modeling	$\pm 1\text{--}4$	$\pm 0.07$
Generator modeling	$\pm 1.4$	$\pm 0.05$
EW corrections	$\pm 2$	$\pm 0.06$
PDF	$\pm 3\text{--}4$	$\pm 0.18$
$\mathcal{B}(H \rightarrow \tau\tau)$	$\pm 3\text{--}7$	$\pm 0.17$

background yields and on the shape of the mass distributions,  $M_{\text{MMC}}$  or  $M_{2\text{T}}$  respectively, are evaluated. Table VI shows the systematic uncertainties, their impact on the number of expected events for the signal and the relevant background, and their impact on the postfit signal strength,  $\mu$ , where  $\mu = \sigma/\sigma_{\text{SM}}$  and the value  $\mathcal{B}(H \rightarrow \tau^+\tau^-)$  corresponds to the standard model prediction for  $m_H = 125$  GeV.

Experimental systematic uncertainties arise from uncertainties on trigger efficiencies, particle reconstruction, and identification, as well as uncertainties on the energy scale and resolution of jets, leptons, and  $\tau_{\text{had}}$  candidates. The efficiency-related uncertainties are estimated in data using tag-and-probe techniques. The MC samples used are corrected for differences in these efficiencies between data and simulation and the associated uncertainties are propagated through the analysis. The lepton energy scale uncertainties are measured in data. For  $\tau_{\text{had}}$  candidates, where the uncertainty is dominated by calorimeter response, this is done by fitting the visible  $Z \rightarrow \tau\tau$  mass [27]. The systematic uncertainties due to energy resolution have a negligible impact on the result. Systematic effects from electron- and muon-related uncertainties are smaller in general than those from jets and  $\tau_{\text{had}}$  candidates. The soft-scale  $E_{\text{T}}^{\text{miss}}$  resolution accounts for low- $p_{\text{T}}$  energy deposits that do not contribute to the clustered energy of physics objects ( $e$ ,  $\mu$ ,  $\tau$ , jet). The  $b$ -jet tagging efficiency is measured in data with  $t\bar{t}$  events and has an uncertainty of a few percent, which in turn has a small impact on the prediction of the  $t\bar{t}$  background in the signal region.

The systematic uncertainty on the background from jets misidentified as leptons is estimated for each type of lepton separately. It is assumed to be uncorrelated with all other uncertainties. The uncertainty on the contribution to the background from jets misidentified as  $\tau_{\text{had}}$  is dominated by uncertainty in the fraction of quark- and gluon-initiated jets. This accounts for the potential difference between the fraction of quark-initiated jets in the fake-factor measurement region and the analysis signal region, where the fake factor is applied. Because quark- and gluon-initiated jets can fake  $\tau_{\text{had}}$  candidates at different rates, a difference in their ratio between the fake-factor measurement and signal region would bias the fake factors themselves. The systematic uncertainty is evaluated by varying the ratio of quark- to gluon-initiated jets from half to two times the nominal value, as determined in MC simulation. The systematic uncertainty for the electron fake factor is determined in a way similar to the  $\tau_{\text{had}}$  fake factor, although the compositions of misidentified candidates from jets and photons are varied as opposed to the relative fractions of quark- and gluon-initiated jets.

The uncertainty on the luminosity ( $\pm 2.8\%$ ) derived from beam-separation scans performed in 2012 using the method described in Ref. [51] affects the number of signal and simulated background events.

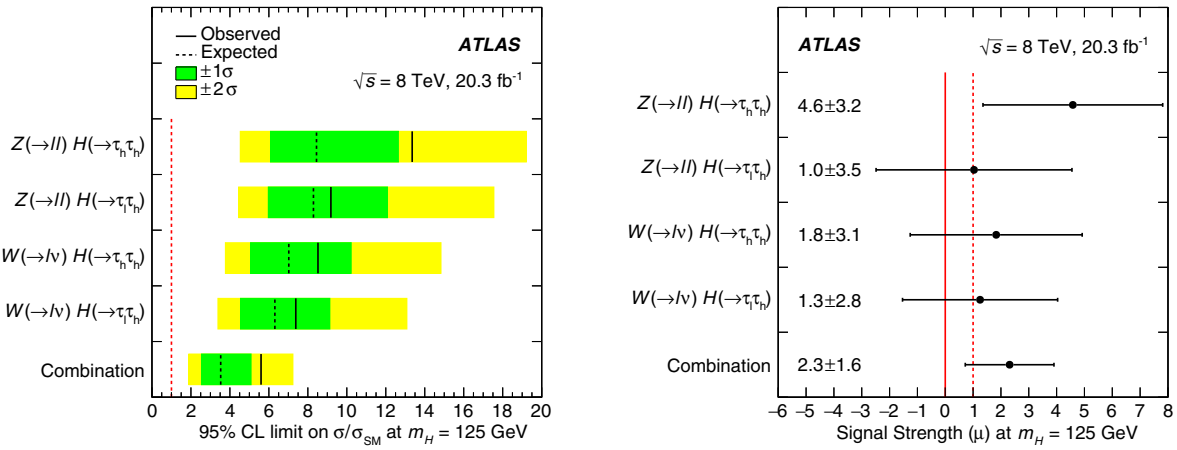


FIG. 3. The combined result for the  $VH$  channels. The 95% C.L. cross section limit is shown for each individual channel on the left. The right figure shows the signal strength in each individual channel, along with the combination.

Theoretical uncertainties are estimated for the signal and for all background contributions derived using MC simulation. Uncertainties relating to higher-order QCD corrections and MC modeling choices are estimated by varying the renormalization and factorization scales, PDF parameterization, and underlying-event model as described in Ref. [52]. The signal samples, generated in QCD LO with PYTHIA8, are normalized using cross sections computed in NNLO in QCD and NLO in electroweak corrections, but kinematic distributions, such as the Higgs boson  $p_T$ , are not reweighted. The HAWK MC program [53], which calculates NLO QCD and NLO electroweak corrections for all the  $VH$  processes, is used to evaluate the resulting systematic uncertainties due to kinematic differences. The impact of the QCD scale choice on the signal acceptance is evaluated in MC simulation before the ATLAS detector simulation is performed, separately for the four analysis channels, by varying the QCD scales in POWHEG+PYTHIA8.

## VIII. RESULTS

The observed signal strength  $\mu$ , is determined from a binned global maximum-likelihood fit to the reconstructed Higgs boson candidate mass distributions, with nuisance parameters  $\vec{\theta}$  corresponding to the systematic uncertainties. The  $M_{2T}$  distribution is used for the  $WH$  topologies and the  $M_{\text{MMC}}$  distribution for the  $ZH$  categories. For each signal and background process, each nuisance parameter is separately tested to determine whether it affects the  $M_{2T}$  or  $M_{\text{MMC}}$  distributions. For background processes only, the effect of a nuisance parameter on the shape of the distributions is neglected if the difference between the up and down variations of the yield in all bins of the distribution is less than 10% of the total background statistical error. Overall systematic uncertainties that differ from the nominal by less than 0.5% are not considered. The only exception is the treatment of systematic uncertainties

due to theoretical aspects, which are fully considered even though they have a small overall impact on the fit.

The expected numbers of signal and background events in each bin are functions of  $\theta$ . The test statistic  $q_\mu$  is then constructed according to the profile likelihood ratio,

$q_\mu = -2 \ln[\mathcal{L}(\mu, \hat{\theta})/\mathcal{L}(\hat{\mu}, \hat{\theta})]$ , where the numerator  $\mathcal{L}(\mu, \hat{\theta})$  is the conditional maximum likelihood with  $\hat{\theta}$  the value of the nuisance parameters that maximize  $\mathcal{L}$  for a given  $\mu$  and the denominator  $\mathcal{L}(\hat{\mu}, \hat{\theta})$  is the unconditional maximum likelihood. This test statistic is used to measure the compatibility of the background-only hypothesis with the observed data and for setting limits derived with the  $CL_s$  method [54,55]. To quantify this compatibility, a significance is calculated, giving the probability of obtaining  $q_\mu$  if  $\mu = 1$  is the true signal strength.

The measured signal strength, normalized to the SM expectation, is  $\mu = 2.3 \pm 1.6$  for  $m_H = 125$  GeV. The 95% confidence-level (C.L.) upper limits for each of the four channels and their associated signal strengths are shown in Fig. 3. The expected and observed significances for each of the four channels are shown in Table VII.

The overall 95% C.L. limit on the observed ratio of the cross section to the SM prediction is 5.6 at  $m_H = 125$  GeV, which is above the expected values of 3.5 if no signal is assumed and 3.7 if signal is included, but is consistent

TABLE VII. The expected and observed significances for the four channels.

Channel	Expected significance	Observed significance
$W \rightarrow \mu\nu/ev, H \rightarrow \tau_{\text{lep}}\tau_{\text{had}}$	$0.36\sigma$	$0.44\sigma$
$W \rightarrow \mu\nu/ev, H \rightarrow \tau_{\text{had}}\tau_{\text{had}}$	$0.32\sigma$	$0.60\sigma$
$Z \rightarrow \mu\mu/ee, H \rightarrow \tau_{\text{lep}}\tau_{\text{had}}$	$0.28\sigma$	$0.29\sigma$
$Z \rightarrow \mu\mu/ee, H \rightarrow \tau_{\text{had}}\tau_{\text{had}}$	$0.32\sigma$	$1.38\sigma$

within the uncertainties of the expected limit. The weaker limit in the data comes mostly from the slight excesses seen in the two channels with  $H \rightarrow \tau_{\text{had}} \tau_{\text{had}}$ .

## IX. CONCLUSION

The analysis presented in this paper, a search for the associated production of the SM Higgs boson with a vector boson where the Higgs boson decays to a pair of tau leptons, is based on  $20.3 \text{ fb}^{-1}$  of LHC proton-proton collisions recorded by the ATLAS experiment at the center-of-mass energy  $\sqrt{s} = 8 \text{ TeV}$ . The overall 95% C.L. upper limit on the ratio of the observed cross section to the SM predicted cross section, at 5.6, is higher than the expected values of 3.5 if no signal is assumed and 3.7 if signal is included, but is consistent within the statistics and uncertainties of the analysis. The measured signal strength, normalized to the standard model expectation for a Higgs boson of  $m_H = 125 \text{ GeV}$ , is  $\mu = 2.3 \pm 1.6$ .

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G. Aad,<sup>85</sup> B. Abbott,<sup>113</sup> J. Abdallah,<sup>151</sup> O. Abidinov,<sup>11</sup> R. Aben,<sup>107</sup> M. Abolins,<sup>90</sup> O. S. AbouZeid,<sup>158</sup> H. Abramowicz,<sup>153</sup> H. Abreu,<sup>152</sup> R. Abreu,<sup>116</sup> Y. Abulaiti,<sup>146a,146b</sup> B. S. Acharya,<sup>164a,164b</sup> L. Adamczyk,<sup>38a</sup> D. L. Adams,<sup>25</sup> J. Adelman,<sup>108</sup> S. Adomeit,<sup>100</sup> T. Adye,<sup>131</sup> A. A. Affolder,<sup>74</sup> T. Agatonovic-Jovin,<sup>13</sup> J. Agricola,<sup>54</sup> J. A. Aguilar-Saavedra,<sup>126a,126f</sup> S. P. Ahlen,<sup>22</sup> F. Ahmadov,<sup>65,c</sup> G. Aielli,<sup>133a,133b</sup> H. Akerstedt,<sup>146a,146b</sup> T. P. A. Åkesson,<sup>81</sup> A. V. Akimov,<sup>96</sup> G. L. Alberghi,<sup>20a,20b</sup> J. Albert,<sup>169</sup> S. Albrand,<sup>55</sup> M. J. Alconada Verzini,<sup>71</sup> M. Aleksa,<sup>30</sup> I. N. Aleksandrov,<sup>65</sup> C. Alexa,<sup>26b</sup> G. Alexander,<sup>153</sup> T. Alexopoulos,<sup>10</sup> M. Alhroob,<sup>113</sup> G. Alimonti,<sup>91a</sup> L. Alio,<sup>85</sup> J. Alison,<sup>31</sup> S. P. Alkire,<sup>35</sup> B. M. M. Allbrooke,<sup>149</sup> P. P. Allport,<sup>18</sup> A. Aloisio,<sup>104a,104b</sup> A. Alonso,<sup>36</sup> F. Alonso,<sup>71</sup> C. Alpigiani,<sup>76</sup> A. Altheimer,<sup>35</sup> B. Alvarez Gonzalez,<sup>30</sup> D. Álvarez Piqueras,<sup>167</sup> M. G. Alvigi,<sup>104a,104b</sup> B. T. Amadio,<sup>15</sup> K. Amako,<sup>66</sup> Y. Amaral Coutinho,<sup>24a</sup> C. Amelung,<sup>23</sup> D. Amidei,<sup>89</sup> S. P. Amor Dos Santos,<sup>126a,126c</sup> A. Amorim,<sup>126a,126b</sup> S. Amoroso,<sup>48</sup> N. Amram,<sup>153</sup> G. Amundsen,<sup>23</sup> C. Anastopoulos,<sup>139</sup> L. S. Ancu,<sup>49</sup> N. Andari,<sup>108</sup> T. Andeen,<sup>35</sup> C. F. Anders,<sup>58b</sup> G. Anders,<sup>30</sup> J. K. Anders,<sup>74</sup> K. J. Anderson,<sup>31</sup> A. Andreazza,<sup>91a,91b</sup> V. Andrei,<sup>58a</sup> S. Angelidakis,<sup>9</sup> I. Angelozzi,<sup>107</sup> P. Anger,<sup>44</sup> A. Angerami,<sup>35</sup> F. Anghinolfi,<sup>30</sup> A. V. Anisenkov,<sup>109,d</sup> N. Anjos,<sup>12</sup> A. Annovi,<sup>124a,124b</sup> M. Antonelli,<sup>47</sup> A. Antonov,<sup>98</sup> J. Antos,<sup>144b</sup> F. Anulli,<sup>132a</sup> M. Aoki,<sup>66</sup> L. Aperio Bella,<sup>18</sup> G. Arabidze,<sup>90</sup> Y. Arai,<sup>66</sup> J. P. Araque,<sup>126a</sup> A. T. H. Arce,<sup>45</sup> F. A. Arduh,<sup>71</sup> J. F. Arguin,<sup>95</sup> S. Argyropoulos,<sup>63</sup> M. Arik,<sup>19a</sup> A. J. Armbruster,<sup>30</sup> O. Arnaez,<sup>30</sup> V. Arnal,<sup>82</sup> H. Arnold,<sup>48</sup> M. Arratia,<sup>28</sup> O. Arslan,<sup>21</sup> A. Artamonov,<sup>97</sup> G. Artoni,<sup>23</sup> S. Asai,<sup>155</sup> N. Asbah,<sup>42</sup> A. Ashkenazi,<sup>153</sup> B. Åsman,<sup>146a,146b</sup> L. Asquith,<sup>149</sup> K. Assamagan,<sup>25</sup> R. Astalos,<sup>144a</sup> M. Atkinson,<sup>165</sup> N. B. Atlay,<sup>141</sup> K. Augsten,<sup>128</sup> M. Auresseu,<sup>145b</sup> G. Avolio,<sup>30</sup> B. Axen,<sup>15</sup> M. K. Ayoub,<sup>117</sup> G. Azuelos,<sup>95,e</sup> M. A. Baak,<sup>30</sup> A. E. Baas,<sup>58a</sup> M. J. Baca,<sup>18</sup> C. Bacci,<sup>134a,134b</sup> H. Bachacou,<sup>136</sup> K. Bachas,<sup>154</sup> M. Backes,<sup>30</sup> M. Backhaus,<sup>30</sup> P. Bagiacchi,<sup>132a,132b</sup> P. Bagnaia,<sup>132a,132b</sup> Y. Bai,<sup>33a</sup> T. Bain,<sup>35</sup> J. T. Baines,<sup>131</sup> O. K. Baker,<sup>176</sup> E. M. Baldin,<sup>109,d</sup> P. Balek,<sup>129</sup> T. Balestri,<sup>148</sup> F. Balli,<sup>84</sup> W. K. Balunas,<sup>122</sup> E. Banas,<sup>39</sup> Sw. Banerjee,<sup>173</sup> A. A. E. Bannoura,<sup>175</sup> H. S. Bansil,<sup>18</sup> L. Barak,<sup>30</sup> E. L. Barberio,<sup>88</sup> D. Barberis,<sup>50a,50b</sup> M. Barbero,<sup>85</sup> T. Barillari,<sup>101</sup> M. Barisonzi,<sup>164a,164b</sup> T. Barklow,<sup>143</sup> N. Barlow,<sup>28</sup> S. L. Barnes,<sup>84</sup> B. M. Barnett,<sup>131</sup> R. M. Barnett,<sup>15</sup> Z. Barnovska,<sup>5</sup> A. Baroncelli,<sup>134a</sup> G. Barone,<sup>23</sup> A. J. Barr,<sup>120</sup> F. Barreiro,<sup>82</sup> J. Barreiro Guimarães da Costa,<sup>57</sup> R. Bartoldus,<sup>143</sup> A. E. Barton,<sup>72</sup> P. Bartos,<sup>144a</sup> A. Basalaeu,<sup>123</sup> A. Bassalat,<sup>117</sup> A. Basye,<sup>165</sup> R. L. Bates,<sup>53</sup> S. J. Batista,<sup>158</sup> J. R. Batley,<sup>28</sup> M. Battaglia,<sup>137</sup> M. Bause,<sup>132a,132b</sup> F. Bauer,<sup>136</sup> H. S. Bawa,<sup>143,f</sup> J. B. Beacham,<sup>111</sup> M. D. Beattie,<sup>72</sup> T. Beau,<sup>80</sup> P. H. Beauchemin,<sup>161</sup> R. Beccherle,<sup>124a,124b</sup> P. Bechtel,<sup>21</sup> H. P. Beck,<sup>17,g</sup> K. Becker,<sup>120</sup> M. Becker,<sup>83</sup> M. Beckingham,<sup>170</sup> C. Becot,<sup>117</sup> A. J. Beddall,<sup>19b</sup> A. Beddall,<sup>19b</sup> V. A. Bednyakov,<sup>65</sup> C. P. Bee,<sup>148</sup> L. J. Beemster,<sup>107</sup> T. A. Beermann,<sup>30</sup> M. Begel,<sup>25</sup> J. K. Behr,<sup>120</sup> C. Belanger-Champagne,<sup>87</sup> W. H. Bell,<sup>49</sup> G. Bella,<sup>153</sup> L. Bellagamba,<sup>20a</sup> A. Bellerive,<sup>29</sup> M. Bellomo,<sup>86</sup> K. Belotskiy,<sup>98</sup> O. Beltramello,<sup>30</sup> O. Benary,<sup>153</sup> D. Bencheikroun,<sup>135a</sup> M. Bender,<sup>100</sup> K. Bendtz,<sup>146a,146b</sup> N. Benekos,<sup>10</sup> Y. Benhammou,<sup>153</sup> E. Benhar Noccioli,<sup>49</sup> J. A. Benitez Garcia,<sup>159b</sup> D. P. Benjamin,<sup>45</sup> J. R. Bensinger,<sup>23</sup> S. Bentvelsen,<sup>107</sup> L. Beresford,<sup>120</sup> M. Beretta,<sup>47</sup> D. Berge,<sup>107</sup> E. Bergeas Kuutmann,<sup>166</sup> N. Berger,<sup>5</sup> F. Berghaus,<sup>169</sup> J. Beringer,<sup>15</sup> C. Bernard,<sup>22</sup> N. R. Bernard,<sup>86</sup> C. Bernius,<sup>110</sup> F. U. Bernlochner,<sup>21</sup> T. Berry,<sup>77</sup> P. Berta,<sup>129</sup> C. Bertella,<sup>83</sup> G. Bertoli,<sup>146a,146b</sup> F. Bertolucci,<sup>124a,124b</sup> C. Bertsche,<sup>113</sup> D. Bertsche,<sup>113</sup> M. I. Besana,<sup>91a</sup> G. J. Besjes,<sup>36</sup> O. Bessidskaia Bylund,<sup>146a,146b</sup> M. Bessner,<sup>42</sup> N. Besson,<sup>136</sup> C. Betancourt,<sup>48</sup> S. Bethke,<sup>101</sup> A. J. Bevan,<sup>76</sup> W. Bhimji,<sup>15</sup> R. M. Bianchi,<sup>125</sup> L. Bianchini,<sup>23</sup> M. Bianco,<sup>30</sup> O. Biebel,<sup>100</sup> D. Biedermann,<sup>16</sup> S. P. Bieniek,<sup>78</sup> M. Biglietti,<sup>134a</sup> J. Bilbao De Mendizabal,<sup>49</sup> H. Bilokon,<sup>47</sup> M. Bindi,<sup>54</sup> S. Binet,<sup>117</sup> A. Bingul,<sup>19b</sup> C. Bini,<sup>132a,132b</sup> S. Biondi,<sup>20a,20b</sup> D. M. Bjergaard,<sup>45</sup> C. W. Black,<sup>150</sup> J. E. Black,<sup>143</sup> K. M. Black,<sup>22</sup> D. Blackburn,<sup>138</sup> R. E. Blair,<sup>6</sup> J.-B. Blanchard,<sup>136</sup> J. E. Blanco,<sup>77</sup> T. Blazek,<sup>144a</sup> I. Bloch,<sup>42</sup> C. Blocker,<sup>23</sup> W. Blum,<sup>83,a</sup> U. Blumenschein,<sup>54</sup> G. J. Bobbink,<sup>107</sup> V. S. Bobrovnikov,<sup>109,d</sup> S. S. Bocchetta,<sup>81</sup> A. Bocci,<sup>45</sup> C. Bock,<sup>100</sup> M. Boehler,<sup>48</sup> J. A. Bogaerts,<sup>30</sup> D. Bogavac,<sup>13</sup> A. G. Bogdanchikov,<sup>109</sup> C. Bohm,<sup>146a</sup> V. Boisvert,<sup>77</sup> T. Bold,<sup>38a</sup> V. Boidea,<sup>26b</sup> A. S. Boldyrev,<sup>99</sup> M. Bomben,<sup>80</sup> M. Bona,<sup>76</sup> M. Boonekamp,<sup>136</sup> A. Borisov,<sup>130</sup> G. Borissov,<sup>72</sup> S. Borroni,<sup>42</sup>



J. Bortfeldt,<sup>100</sup> V. Bortolotto,<sup>60a,60b,60c</sup> K. Bos,<sup>107</sup> D. Boscherini,<sup>20a</sup> M. Bosman,<sup>12</sup> J. Boudreau,<sup>125</sup> J. Bouffard,<sup>2</sup> E. V. Bouhova-Thacker,<sup>72</sup> D. Boumediene,<sup>34</sup> C. Bourdarios,<sup>117</sup> N. Bousson,<sup>114</sup> S. K. Boutle,<sup>53</sup> A. Boveia,<sup>30</sup> J. Boyd,<sup>30</sup> I. R. Boyko,<sup>65</sup> I. Bozic,<sup>13</sup> J. Bracinik,<sup>18</sup> A. Brandt,<sup>8</sup> G. Brandt,<sup>54</sup> O. Brandt,<sup>58a</sup> U. Bratzler,<sup>156</sup> B. Brau,<sup>86</sup> J. E. Brau,<sup>116</sup> H. M. Braun,<sup>175,a</sup> S. F. Brazzale,<sup>164a,164c</sup> W. D. Breaden Madden,<sup>53</sup> K. Brendlinger,<sup>122</sup> A. J. Brennan,<sup>88</sup> L. Brenner,<sup>107</sup> R. Brenner,<sup>166</sup> S. Bressler,<sup>172</sup> K. Bristow,<sup>145c</sup> T. M. Bristow,<sup>46</sup> D. Britton,<sup>53</sup> D. Britzger,<sup>42</sup> F. M. Brochu,<sup>28</sup> I. Brock,<sup>21</sup> R. Brock,<sup>90</sup> J. Bronner,<sup>101</sup> G. Brooijmans,<sup>35</sup> T. Brooks,<sup>77</sup> W. K. Brooks,<sup>32b</sup> J. Brosamer,<sup>15</sup> E. Brost,<sup>116</sup> J. Brown,<sup>55</sup> P. A. Bruckman de Renstrom,<sup>39</sup> D. Bruncko,<sup>144b</sup> R. Bruneliere,<sup>48</sup> A. Bruni,<sup>20a</sup> G. Bruni,<sup>20a</sup> M. Bruschi,<sup>20a</sup> N. Bruscino,<sup>21</sup> L. Bryngemark,<sup>81</sup> T. Buanes,<sup>14</sup> Q. Buat,<sup>142</sup> P. Buchholz,<sup>141</sup> A. G. Buckley,<sup>53</sup> S. I. Buda,<sup>26b</sup> I. A. Budagov,<sup>65</sup> F. Buehrer,<sup>48</sup> L. Bugge,<sup>119</sup> M. K. Bugge,<sup>119</sup> O. Bulekov,<sup>98</sup> D. Bullock,<sup>8</sup> H. Burckhart,<sup>30</sup> S. Burdin,<sup>74</sup> C. D. Burgard,<sup>48</sup> B. Burghgrave,<sup>108</sup> S. Burke,<sup>131</sup> I. Burmeister,<sup>43</sup> E. Busato,<sup>34</sup> D. Büscher,<sup>48</sup> V. Büscher,<sup>83</sup> P. Bussey,<sup>53</sup> J. M. Butler,<sup>22</sup> A. I. Butt,<sup>3</sup> C. M. Buttar,<sup>53</sup> J. M. Butterworth,<sup>78</sup> P. Butti,<sup>107</sup> W. Buttinger,<sup>25</sup> A. Buzatu,<sup>53</sup> A. R. Buzykaev,<sup>109,d</sup> S. Cabrera Urbán,<sup>167</sup> D. Caforio,<sup>128</sup> V. M. Cairo,<sup>37a,37b</sup> O. Cakir,<sup>4a</sup> N. Calace,<sup>49</sup> P. Calafiura,<sup>15</sup> A. Calandri,<sup>136</sup> G. Calderini,<sup>80</sup> P. Calfayan,<sup>100</sup> L. P. Caloba,<sup>24a</sup> D. Calvet,<sup>34</sup> S. Calvet,<sup>34</sup> R. Camacho Toro,<sup>31</sup> S. Camarda,<sup>42</sup> P. Camarri,<sup>133a,133b</sup> D. Cameron,<sup>119</sup> R. Caminal Armadans,<sup>165</sup> S. Campana,<sup>30</sup> M. Campanelli,<sup>78</sup> A. Campoverde,<sup>148</sup> V. Canale,<sup>104a,104b</sup> A. Canepa,<sup>159a</sup> M. Cano Bret,<sup>33e</sup> J. Cantero,<sup>82</sup> R. Cantrill,<sup>126a</sup> T. Cao,<sup>40</sup> M. D. M. Capeans Garrido,<sup>30</sup> I. Caprini,<sup>26b</sup> M. Caprini,<sup>26b</sup> M. Capua,<sup>37a,37b</sup> R. Caputo,<sup>83</sup> R. Cardarelli,<sup>133a</sup> F. Cardillo,<sup>48</sup> T. Carli,<sup>30</sup> G. Carlino,<sup>104a</sup> L. Carminati,<sup>91a,91b</sup> S. Caron,<sup>106</sup> E. Carquin,<sup>32a</sup> G. D. Carrillo-Montoya,<sup>30</sup> J. R. Carter,<sup>28</sup> J. Carvalho,<sup>126a,126c</sup> D. Casadei,<sup>78</sup> M. P. Casado,<sup>12</sup> M. Casolino,<sup>12</sup> E. Castaneda-Miranda,<sup>145a</sup> A. Castelli,<sup>107</sup> V. Castillo Gimenez,<sup>167</sup> N. F. Castro,<sup>126a,h</sup> P. Catastini,<sup>57</sup> A. Catinaccio,<sup>30</sup> J. R. Catmore,<sup>119</sup> A. Cattai,<sup>30</sup> J. Caudron,<sup>83</sup> V. Cavaliere,<sup>165</sup> D. Cavalli,<sup>91a</sup> M. Cavalli-Sforza,<sup>12</sup> V. Cavadini,<sup>124a,124b</sup> F. Ceradini,<sup>134a,134b</sup> B. C. Cerio,<sup>45</sup> K. Cerny,<sup>129</sup> A. S. Cerqueira,<sup>24b</sup> A. Cerri,<sup>149</sup> L. Cerrito,<sup>76</sup> F. Cerutti,<sup>15</sup> M. Cerv,<sup>30</sup> A. Cervelli,<sup>17</sup> S. A. Cetin,<sup>19c</sup> A. Chafaq,<sup>135a</sup> D. Chakraborty,<sup>108</sup> I. Chalupkova,<sup>129</sup> P. Chang,<sup>165</sup> J. D. Chapman,<sup>28</sup> D. G. Charlton,<sup>18</sup> C. C. Chau,<sup>158</sup> C. A. Chavez Barajas,<sup>149</sup> S. Cheatham,<sup>152</sup> A. Chegwidan,<sup>90</sup> S. Chekanov,<sup>6</sup> S. V. Chekulaev,<sup>159a</sup> G. A. Chelkov,<sup>65,i</sup> M. A. Chelstowska,<sup>89</sup> C. Chen,<sup>64</sup> H. Chen,<sup>25</sup> K. Chen,<sup>148</sup> L. Chen,<sup>33d,j</sup> S. Chen,<sup>33c</sup> S. Chen,<sup>155</sup> X. Chen,<sup>33f</sup> Y. Chen,<sup>67</sup> H. C. Cheng,<sup>89</sup> Y. Cheng,<sup>31</sup> A. Cheplakov,<sup>65</sup> E. Cheremushkina,<sup>130</sup> R. Cherkaoui El Moursli,<sup>135e</sup> V. Chernyatin,<sup>25,a</sup> E. Cheu,<sup>7</sup> L. Chevalier,<sup>136</sup> V. Chiarella,<sup>47</sup> G. Chiarelli,<sup>124a,124b</sup> G. Chiodini,<sup>73a</sup> A. S. Chisholm,<sup>18</sup> R. T. Chislett,<sup>78</sup> A. Chitan,<sup>26b</sup> M. V. Chizhov,<sup>65</sup> K. Choi,<sup>61</sup> S. Chouridou,<sup>9</sup> B. K. B. Chow,<sup>100</sup> V. Christodoulou,<sup>78</sup> D. Chromek-Burckhart,<sup>30</sup> J. Chudoba,<sup>127</sup> A. J. Chuinard,<sup>87</sup> J. J. Chwastowski,<sup>39</sup> L. Chytka,<sup>115</sup> G. Ciapetti,<sup>132a,132b</sup> A. K. Ciftci,<sup>4a</sup> D. Cinca,<sup>53</sup> V. Cindro,<sup>75</sup> I. A. Cioara,<sup>21</sup> A. Ciocio,<sup>15</sup> F. Ciotto,<sup>104a,104b</sup> Z. H. Citron,<sup>172</sup> M. Ciubancan,<sup>26b</sup> A. Clark,<sup>49</sup> B. L. Clark,<sup>57</sup> P. J. Clark,<sup>46</sup> R. N. Clarke,<sup>15</sup> W. Cleland,<sup>125</sup> C. Clement,<sup>146a,146b</sup> Y. Coadou,<sup>85</sup> M. Cobal,<sup>164a,164c</sup> A. Coccaro,<sup>49</sup> J. Cochran,<sup>64</sup> L. Coffey,<sup>23</sup> J. G. Cogan,<sup>143</sup> L. Colasurdo,<sup>106</sup> B. Cole,<sup>35</sup> S. Cole,<sup>108</sup> A. P. Colijn,<sup>107</sup> J. Collot,<sup>55</sup> T. Colombo,<sup>58c</sup> G. Compostella,<sup>101</sup> P. Conde Muño,<sup>126a,126b</sup> E. Coniavitis,<sup>48</sup> S. H. Connell,<sup>145b</sup> I. A. Connelly,<sup>77</sup> V. Consorti,<sup>48</sup> S. Constantinescu,<sup>26b</sup> C. Conta,<sup>121a,121b</sup> G. Conti,<sup>30</sup> F. Conventi,<sup>104a,k</sup> M. Cooke,<sup>15</sup> B. D. Cooper,<sup>78</sup> A. M. Cooper-Sarkar,<sup>120</sup> T. Cornelissen,<sup>175</sup> M. Corradi,<sup>20a</sup> F. Corriveau,<sup>87,l</sup> A. Corso-Radu,<sup>163</sup> A. Cortes-Gonzalez,<sup>12</sup> G. Cortiana,<sup>101</sup> G. Costa,<sup>91a</sup> M. J. Costa,<sup>167</sup> D. Costanzo,<sup>139</sup> D. Côté,<sup>8</sup> G. Cottin,<sup>28</sup> G. Cowan,<sup>77</sup> B. E. Cox,<sup>84</sup> K. Cranmer,<sup>110</sup> G. Cree,<sup>29</sup> S. Crépe-Renaudin,<sup>55</sup> F. Crescioli,<sup>80</sup> W. A. Cribbs,<sup>146a,146b</sup> M. Crispin Ortuzar,<sup>120</sup> M. Cristinziani,<sup>21</sup> V. Croft,<sup>106</sup> G. Crosetti,<sup>37a,37b</sup> T. Cuhadar Donszelmann,<sup>139</sup> J. Cummings,<sup>176</sup> M. Curatolo,<sup>47</sup> J. Cúth,<sup>83</sup> C. Cuthbert,<sup>150</sup> H. Czirr,<sup>141</sup> P. Czodrowski,<sup>3</sup> S. D'Auria,<sup>53</sup> M. D'Onofrio,<sup>74</sup> M. J. Da Cunha Sargedas De Sousa,<sup>126a,126b</sup> C. Da Via,<sup>84</sup> W. Dabrowski,<sup>38a</sup> A. Dafinca,<sup>120</sup> T. Dai,<sup>89</sup> O. Dale,<sup>14</sup> F. Dallaire,<sup>95</sup> C. Dallapiccola,<sup>86</sup> M. Dam,<sup>36</sup> J. R. Dandoy,<sup>31</sup> N. P. Dang,<sup>48</sup> A. C. Daniells,<sup>18</sup> M. Danninger,<sup>168</sup> M. Dano Hoffmann,<sup>136</sup> V. Dao,<sup>48</sup> G. Darbo,<sup>50a</sup> S. Darmora,<sup>8</sup> J. Dassoulas,<sup>3</sup> A. Dattagupta,<sup>61</sup> W. Davey,<sup>21</sup> C. David,<sup>169</sup> T. Davidek,<sup>129</sup> E. Davies,<sup>120,m</sup> M. Davies,<sup>153</sup> P. Davison,<sup>78</sup> Y. 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Delmastro,<sup>5</sup> P. A. Delsart,<sup>55</sup> C. Deluca,<sup>107</sup> D. A. DeMarco,<sup>158</sup> S. Demers,<sup>176</sup> M. Demichev,<sup>65</sup> A. Demilly,<sup>80</sup> S. P. Denisov,<sup>130</sup> D. Derendarz,<sup>39</sup> J. E. Derkaoui,<sup>135d</sup> F. Derue,<sup>80</sup> P. Dervan,<sup>74</sup> K. Desch,<sup>21</sup> C. Deterre,<sup>42</sup> P. O. Deviveiros,<sup>30</sup> A. Dewhurst,<sup>131</sup> S. Dhaliwal,<sup>23</sup> A. Di Ciaccio,<sup>133a,133b</sup> L. Di Ciaccio,<sup>5</sup> A. Di Domenico,<sup>132a,132b</sup>

- C. Di Donato,<sup>104a,104b</sup> A. Di Girolamo,<sup>30</sup> B. Di Girolamo,<sup>30</sup> A. Di Mattia,<sup>152</sup> B. Di Micco,<sup>134a,134b</sup> R. Di Nardo,<sup>47</sup>  
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 E. B. Diehl,<sup>89</sup> J. Dietrich,<sup>16</sup> S. Diglio,<sup>85</sup> A. Dimitrievska,<sup>13</sup> J. Dingfelder,<sup>21</sup> P. Dita,<sup>26b</sup> S. Dita,<sup>26b</sup> F. Dittus,<sup>30</sup> F. Djama,<sup>85</sup>  
 T. Djobava,<sup>51b</sup> J. I. Djuvsland,<sup>58a</sup> M. A. B. do Vale,<sup>24c</sup> D. Dobos,<sup>30</sup> M. Dobre,<sup>26b</sup> C. Doglioni,<sup>81</sup> T. Dohmae,<sup>155</sup>  
 J. Dolejsi,<sup>129</sup> Z. Dolezal,<sup>129</sup> B. A. Dolgoshein,<sup>98a</sup> M. Donadelli,<sup>24d</sup> S. Donati,<sup>124a,124b</sup> P. Dondero,<sup>121a,121b</sup> J. Donini,<sup>34</sup>  
 J. Dopke,<sup>131</sup> A. Doria,<sup>104a</sup> M. T. Dova,<sup>71</sup> A. T. Doyle,<sup>53</sup> E. Drechsler,<sup>54</sup> M. Dris,<sup>10</sup> E. Dubreuil,<sup>34</sup> E. Duchovni,<sup>172</sup>  
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 H. Duran Yildiz,<sup>4a</sup> M. Düren,<sup>52</sup> A. Durglishvili,<sup>51b</sup> D. Duschinger,<sup>44</sup> M. Dyndal,<sup>38a</sup> C. Eckardt,<sup>42</sup> K. M. Ecker,<sup>101</sup>  
 R. C. Edgar,<sup>89</sup> W. Edson,<sup>2</sup> N. C. Edwards,<sup>46</sup> W. Ehrenfeld,<sup>21</sup> T. Eifert,<sup>30</sup> G. Eigen,<sup>14</sup> K. Einsweiler,<sup>15</sup> T. Ekelof,<sup>166</sup>  
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 D. Emeliyanov,<sup>131</sup> Y. Enari,<sup>155</sup> O. C. Endner,<sup>83</sup> M. Endo,<sup>118</sup> J. Erdmann,<sup>43</sup> A. Ereditato,<sup>17</sup> G. Ernis,<sup>175</sup> J. Ernst,<sup>2</sup>  
 M. Ernst,<sup>25</sup> S. Errede,<sup>165</sup> E. Ertel,<sup>83</sup> M. Escalier,<sup>117</sup> H. Esch,<sup>43</sup> C. Escobar,<sup>125</sup> B. Esposito,<sup>47</sup> A. I. Etienne,<sup>136</sup>  
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 J. Faltova,<sup>129</sup> Y. Fang,<sup>33a</sup> M. Fanti,<sup>91a,91b</sup> A. Farbin,<sup>8</sup> A. Farilla,<sup>134a</sup> T. Farooque,<sup>12</sup> S. Farrell,<sup>15</sup> S. M. Farrington,<sup>170</sup>  
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 A. B. Fenyuk,<sup>130</sup> L. Feremenga,<sup>8</sup> P. Fernandez Martinez,<sup>167</sup> S. Fernandez Perez,<sup>30</sup> J. Ferrando,<sup>53</sup> A. Ferrari,<sup>166</sup>  
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 M. Fiascaris,<sup>31</sup> F. Fiedler,<sup>83</sup> A. Filipčič,<sup>75</sup> M. Filipuzzi,<sup>42</sup> F. Filthaut,<sup>106</sup> M. Fincke-Keeler,<sup>169</sup> K. D. Finelli,<sup>150</sup>  
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 E. A. Fitzgerald,<sup>23</sup> N. Flaschel,<sup>42</sup> I. Fleck,<sup>141</sup> P. Fleischmann,<sup>89</sup> S. Fleischmann,<sup>175</sup> G. T. Fletcher,<sup>139</sup> G. Fletcher,<sup>76</sup>  
 R. R. M. Fletcher,<sup>122</sup> T. Flick,<sup>175</sup> A. Floderus,<sup>81</sup> L. R. Flores Castillo,<sup>60a</sup> M. J. Flowerdew,<sup>101</sup> A. Formica,<sup>136</sup> A. Forti,<sup>84</sup>  
 D. Fournier,<sup>117</sup> H. Fox,<sup>72</sup> S. Fracchia,<sup>12</sup> P. Francavilla,<sup>80</sup> M. Franchini,<sup>20a,20b</sup> D. Francis,<sup>30</sup> L. Franconi,<sup>119</sup> M. Franklin,<sup>57</sup>  
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 C. Galea,<sup>106</sup> B. Galhardo,<sup>126a,126c</sup> E. J. Gallas,<sup>120</sup> B. J. Gallop,<sup>131</sup> P. Gallus,<sup>128</sup> G. Galster,<sup>36</sup> K. K. Gan,<sup>111</sup> J. Gao,<sup>33b,85</sup>  
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 Z. Gecse,<sup>168</sup> C. N. P. Gee,<sup>131</sup> Ch. Geich-Gimbel,<sup>21</sup> M. P. Geisler,<sup>58a</sup> C. Gemme,<sup>50a</sup> M. H. Genest,<sup>55</sup> S. Gentile,<sup>132a,132b</sup>  
 M. George,<sup>54</sup> S. George,<sup>77</sup> D. Gerbaudo,<sup>163</sup> A. Gershon,<sup>153</sup> S. Ghasemi,<sup>141</sup> H. Ghazlane,<sup>135b</sup> B. Giacobbe,<sup>20a</sup>  
 S. Giagu,<sup>132a,132b</sup> V. Giangiobbe,<sup>12</sup> P. Giannetti,<sup>124a,124b</sup> B. Gibbard,<sup>25</sup> S. M. Gibson,<sup>77</sup> M. Gilchriese,<sup>15</sup> T. P. S. Gillam,<sup>28</sup>  
 D. Gillberg,<sup>30</sup> G. Gilles,<sup>34</sup> D. M. Gingrich,<sup>3e</sup> N. Giokaris,<sup>9</sup> M. P. Giordani,<sup>164a,164c</sup> F. M. Giorgi,<sup>20a</sup> F. M. Giorgi,<sup>16</sup>  
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 D. Goujdami,<sup>135c</sup> A. G. Goussiou,<sup>138</sup> N. Govender,<sup>145b</sup> E. Gozani,<sup>152</sup> H. M. X. Grabas,<sup>137</sup> L. Graber,<sup>54</sup>  
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 Y. Guo,<sup>33b,q</sup> S. Gupta,<sup>120</sup> G. Gustavino,<sup>132a,132b</sup> P. Gutierrez,<sup>113</sup> N. G. Gutierrez Ortiz,<sup>78</sup> C. Gutsche,<sup>44</sup> C. Guyot,<sup>136</sup>  
 C. Gwenlan,<sup>120</sup> C. B. Gwilliam,<sup>74</sup> A. Haas,<sup>110</sup> C. Haber,<sup>15</sup> H. K. Hadavand,<sup>8</sup> N. Haddad,<sup>135e</sup> P. Haefner,<sup>21</sup> S. Hageböck,<sup>21</sup>  
 Z. Hajduk,<sup>39</sup> H. Hakobyan,<sup>177</sup> M. Haleem,<sup>42</sup> J. Haley,<sup>114</sup> D. Hall,<sup>120</sup> G. Halladjian,<sup>90</sup> G. D. Hallowell,<sup>85</sup> K. Hamacher,<sup>175</sup>

- P. Hamal,<sup>115</sup> K. Hamano,<sup>169</sup> A. Hamilton,<sup>145a</sup> G. N. Hamity,<sup>139</sup> P. G. Hamnett,<sup>42</sup> L. Han,<sup>33b</sup> K. Hanagaki,<sup>66,r</sup> K. Hanawa,<sup>155</sup> M. Hance,<sup>15</sup> B. Haney,<sup>122</sup> P. Hanke,<sup>58a</sup> R. Hanna,<sup>136</sup> J. B. Hansen,<sup>36</sup> J. D. Hansen,<sup>36</sup> M. C. Hansen,<sup>21</sup> P. H. Hansen,<sup>36</sup> K. Hara,<sup>160</sup> A. S. Hard,<sup>173</sup> T. Harenberg,<sup>175</sup> F. Hariri,<sup>117</sup> S. Harkusha,<sup>92</sup> R. D. Harrington,<sup>46</sup> P. F. Harrison,<sup>170</sup> F. Hartjes,<sup>107</sup> M. Hasegawa,<sup>67</sup> Y. Hasegawa,<sup>140</sup> A. Hasib,<sup>113</sup> S. Hassani,<sup>136</sup> S. Haug,<sup>17</sup> R. Hauser,<sup>90</sup> L. Hauswald,<sup>44</sup> M. Havranek,<sup>127</sup> C. M. Hawkes,<sup>18</sup> R. J. Hawkings,<sup>30</sup> A. D. Hawkins,<sup>81</sup> T. Hayashi,<sup>160</sup> D. Hayden,<sup>90</sup> C. P. Hays,<sup>120</sup> J. M. Hays,<sup>76</sup> H. S. Hayward,<sup>74</sup> S. J. Haywood,<sup>131</sup> S. J. Head,<sup>18</sup> T. Heck,<sup>83</sup> V. Hedberg,<sup>81</sup> L. Heelan,<sup>8</sup> S. Heim,<sup>122</sup> T. Heim,<sup>175</sup> B. Heinemann,<sup>15</sup> L. Heinrich,<sup>110</sup> J. Hejbal,<sup>127</sup> L. Helary,<sup>22</sup> S. Hellman,<sup>146a,146b</sup> D. Hellmich,<sup>21</sup> C. Helsens,<sup>12</sup> J. Henderson,<sup>120</sup> R. C. W. Henderson,<sup>72</sup> Y. Heng,<sup>173</sup> C. Hengler,<sup>42</sup> S. Henkelmann,<sup>168</sup> A. Henrichs,<sup>176</sup> A. M. Henriques Correia,<sup>30</sup> S. Henrot-Versille,<sup>117</sup> G. H. Herbert,<sup>16</sup> Y. Hernández Jiménez,<sup>167</sup> R. Herrberg-Schubert,<sup>16</sup> G. Herten,<sup>48</sup> R. Hertenberger,<sup>100</sup> L. Hervas,<sup>30</sup> G. G. Hesketh,<sup>78</sup> N. P. Hessey,<sup>107</sup> J. W. Hetherly,<sup>40</sup> R. Hickling,<sup>76</sup> E. Higón-Rodríguez,<sup>167</sup> E. Hill,<sup>169</sup> J. C. Hill,<sup>28</sup> K. H. Hiller,<sup>42</sup> S. J. Hillier,<sup>18</sup> I. Hinchliffe,<sup>15</sup> E. Hines,<sup>122</sup> R. R. Hinman,<sup>15</sup> M. Hirose,<sup>157</sup> D. Hirschbuehl,<sup>175</sup> J. Hobbs,<sup>148</sup> N. Hod,<sup>107</sup> M. C. Hodgkinson,<sup>139</sup> P. Hodgson,<sup>139</sup> A. Hoecker,<sup>30</sup> M. R. Hoefkamp,<sup>105</sup> F. Hoenig,<sup>100</sup> M. Hohlfield,<sup>83</sup> D. Hohn,<sup>21</sup> T. R. Holmes,<sup>15</sup> M. Homann,<sup>43</sup> T. M. Hong,<sup>125</sup> W. H. Hopkins,<sup>116</sup> Y. Horii,<sup>103</sup> A. J. Horton,<sup>142</sup> J.-Y. Hostachy,<sup>55</sup> S. Hou,<sup>151</sup> A. Hoummada,<sup>135a</sup> J. Howard,<sup>120</sup> J. Howarth,<sup>42</sup> M. Hrabovsky,<sup>115</sup> I. Hristova,<sup>16</sup> J. Hrivnac,<sup>117</sup> T. Hryn'ova,<sup>5</sup> A. Hrynevich,<sup>93</sup> C. Hsu,<sup>145c</sup> P. J. Hsu,<sup>151,s</sup> S.-C. Hsu,<sup>138</sup> D. Hu,<sup>35</sup> Q. Hu,<sup>33b</sup> X. Hu,<sup>89</sup> Y. 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Jiang,<sup>33b</sup> S. Jiggins,<sup>78</sup> J. Jimenez Pena,<sup>167</sup> S. Jin,<sup>33a</sup> A. Jinaru,<sup>26b</sup> O. Jinnouchi,<sup>157</sup> M. D. Joergensen,<sup>36</sup> P. Johansson,<sup>139</sup> K. A. Johns,<sup>7</sup> K. Jon-And,<sup>146a,146b</sup> G. Jones,<sup>170</sup> R. W. L. Jones,<sup>72</sup> T. J. Jones,<sup>74</sup> J. Jongmanns,<sup>58a</sup> P. M. Jorge,<sup>126a,126b</sup> K. D. Joshi,<sup>84</sup> J. Jovicevic,<sup>159a</sup> X. Ju,<sup>173</sup> C. A. Jung,<sup>43</sup> P. Jussel,<sup>62</sup> A. Juste Rozas,<sup>12,p</sup> M. Kaci,<sup>167</sup> A. Kaczmarska,<sup>39</sup> M. Kado,<sup>117</sup> H. Kagan,<sup>111</sup> M. Kagan,<sup>143</sup> S. J. Kahn,<sup>85</sup> E. Kajomovitz,<sup>45</sup> C. W. Kalderon,<sup>120</sup> S. Kama,<sup>40</sup> A. Kamenshchikov,<sup>130</sup> N. Kanaya,<sup>155</sup> S. Kaneti,<sup>28</sup> V. A. Kantserov,<sup>98</sup> J. Kanzaki,<sup>66</sup> B. Kaplan,<sup>110</sup> L. S. Kaplan,<sup>173</sup> A. 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Norberg,<sup>113</sup> M. Nordberg,<sup>30</sup> O. Novgorodova,<sup>44</sup> S. Nowak,<sup>101</sup> M. Nozaki,<sup>66</sup> L. Nozka,<sup>115</sup> K. Ntekas,<sup>10</sup> G. Nunes Hanninger,<sup>88</sup> T. Nunnemann,<sup>100</sup> E. Nurse,<sup>78</sup> F. Nuti,<sup>88</sup> B. J. O'Brien,<sup>46</sup> F. O'grady,<sup>7</sup> D. C. O'Neil,<sup>142</sup> V. O'Shea,<sup>53</sup> F. G. Oakham,<sup>29,e</sup> H. Oberlack,<sup>101</sup> T. Obermann,<sup>21</sup> J. Ocariz,<sup>80</sup> A. Ochi,<sup>67</sup> I. Ochoa,<sup>78</sup> J. P. Ochoa-Ricoux,<sup>32a</sup> S. Oda,<sup>70</sup> S. Odaka,<sup>66</sup> H. Ogren,<sup>61</sup> A. Oh,<sup>84</sup> S. H. Oh,<sup>45</sup> C. C. Ohm,<sup>15</sup> H. Ohman,<sup>166</sup> H. Oide,<sup>30</sup> W. Okamura,<sup>118</sup> H. Okawa,<sup>160</sup> Y. Okumura,<sup>31</sup> T. Okuyama,<sup>66</sup> A. Olariu,<sup>26b</sup> S. A. Olivares Pino,<sup>46</sup> D. Oliveira Damazio,<sup>25</sup> E. Oliver Garcia,<sup>167</sup> A. 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Piegai,<sup>27</sup> D. T. Pignotti,<sup>111</sup> J. E. Pilcher,<sup>31</sup> A. D. Pilkington,<sup>84</sup> A. W. J. Pin,<sup>84</sup> J. Pina,<sup>126a,126b,126d</sup> M. Pinamonti,<sup>164a,164c,ff</sup> J. L. Pinfold,<sup>3</sup> A. Pingel,<sup>36</sup> S. Pires,<sup>80</sup> H. Pirumov,<sup>42</sup> M. Pitt,<sup>172</sup> C. Pizio,<sup>91a,91b</sup> L. Plazak,<sup>144a</sup> M.-A. Pleier,<sup>25</sup> V. Pleskot,<sup>129</sup> E. Plotnikova,<sup>65</sup> P. Plucinski,<sup>146a,146b</sup> D. Pluth,<sup>64</sup> R. Poettgen,<sup>146a,146b</sup> L. Poggioli,<sup>117</sup> D. Pohl,<sup>21</sup> G. Polesello,<sup>121a</sup> A. Poley,<sup>42</sup> A. Policicchio,<sup>37a,37b</sup> R. Polifka,<sup>158</sup> A. Polini,<sup>20a</sup> C. S. Pollard,<sup>53</sup> V. Polychronakos,<sup>25</sup> K. Pommès,<sup>30</sup> L. Pontecorvo,<sup>132a</sup> B. G. Pope,<sup>90</sup> G. A. Popeneciu,<sup>26c</sup> D. S. Popovic,<sup>13</sup> A. Poppleton,<sup>30</sup> S. Pospisil,<sup>128</sup> K. 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A. Robichaud-Veronneau,<sup>87</sup> D. Robinson,<sup>28</sup> J. E. M. Robinson,<sup>42</sup> A. Robson,<sup>53</sup> C. Roda,<sup>124a,124b</sup> S. Roe,<sup>30</sup> O. Röhne,<sup>119</sup>  
S. Rolli,<sup>161</sup> A. Romanouk,<sup>98</sup> M. Romano,<sup>20a,20b</sup> S. M. Romano Saez,<sup>34</sup> E. Romero Adam,<sup>167</sup> N. Rompotis,<sup>138</sup>  
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V. Rossetti,<sup>146a,146b</sup> E. Rossi,<sup>104a,104b</sup> L. P. Rossi,<sup>50a</sup> J. H. N. Rosten,<sup>28</sup> R. Rosten,<sup>138</sup> M. Rotaru,<sup>26b</sup> I. Roth,<sup>172</sup>  
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V. I. Rud,<sup>99</sup> C. Rudolph,<sup>44</sup> M. S. Rudolph,<sup>158</sup> F. Rühr,<sup>48</sup> A. Ruiz-Martinez,<sup>30</sup> Z. Rurikova,<sup>48</sup> N. A. Rusakovich,<sup>65</sup>  
A. Ruschke,<sup>100</sup> H. L. Russell,<sup>138</sup> J. P. Rutherford,<sup>7</sup> N. Ruthmann,<sup>48</sup> Y. F. Ryabov,<sup>123</sup> M. Rybar,<sup>165</sup> G. Rybkin,<sup>117</sup>  
N. C. Ryder,<sup>120</sup> A. F. Saavedra,<sup>150</sup> G. Sabato,<sup>107</sup> S. Sacerdoti,<sup>27</sup> A. Saddique,<sup>3</sup> H. F. W. Sadrozinski,<sup>137</sup> R. Sadykov,<sup>65</sup>  
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G. Salamanna,<sup>134a,134b</sup> A. Salamon,<sup>133a</sup> J. E. Salazar Loyola,<sup>32b</sup> M. Saleem,<sup>113</sup> D. Salek,<sup>107</sup> P. H. Sales De Bruin,<sup>138</sup>  
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D. P. C. Sankey,<sup>131</sup> M. Sannino,<sup>50a,50b</sup> A. Sansoni,<sup>47</sup> C. Santoni,<sup>34</sup> R. Santonico,<sup>133a,133b</sup> H. Santos,<sup>126a</sup>  
I. Santoyo Castillo,<sup>149</sup> K. Sapp,<sup>125</sup> A. Sapronov,<sup>65</sup> J. G. Saraiva,<sup>126a,126d</sup> B. Sarrazin,<sup>21</sup> O. Sasaki,<sup>66</sup> Y. Sasaki,<sup>155</sup>  
K. Sato,<sup>160</sup> G. Sauvage,<sup>5a</sup> E. Sauvan,<sup>5</sup> G. Savage,<sup>77</sup> P. Savard,<sup>158,e</sup> C. Sawyer,<sup>131</sup> L. Sawyer,<sup>79,o</sup> J. Saxon,<sup>31</sup> C. Sbarra,<sup>20a</sup>  
A. Sbrizzi,<sup>20a,20b</sup> T. Scanlon,<sup>78</sup> D. A. Scannicchio,<sup>163</sup> M. Scarcella,<sup>150</sup> V. Scarfone,<sup>37a,37b</sup> J. Schaarschmidt,<sup>172</sup>  
P. Schacht,<sup>101</sup> D. Schaefer,<sup>30</sup> R. Schaefer,<sup>42</sup> J. Schaeffer,<sup>83</sup> S. Schaepe,<sup>21</sup> S. Schaetzel,<sup>58b</sup> U. Schäfer,<sup>83</sup> A. C. Schaffer,<sup>117</sup>  
D. Schaile,<sup>100</sup> R. D. Schamberger,<sup>148</sup> V. Scharf,<sup>58a</sup> V. A. Schegelsky,<sup>123</sup> D. Scheirich,<sup>129</sup> M. Schernau,<sup>163</sup> C. Schiavi,<sup>50a,50b</sup>  
C. Schillo,<sup>48</sup> M. Schioppa,<sup>37a,37b</sup> S. Schlenker,<sup>30</sup> K. Schmieden,<sup>30</sup> C. Schmitt,<sup>83</sup> S. Schmitt,<sup>58b</sup> S. Schmitt,<sup>42</sup>  
B. Schneider,<sup>159a</sup> Y. J. Schnellbach,<sup>74</sup> U. Schnoor,<sup>44</sup> L. Schoeffel,<sup>136</sup> A. Schoening,<sup>58b</sup> B. D. Schoenrock,<sup>90</sup> E. Schopf,<sup>21</sup>  
A. L. S. Schorlemmer,<sup>54</sup> M. Schott,<sup>83</sup> D. Schouten,<sup>159a</sup> J. Schovancova,<sup>8</sup> S. Schramm,<sup>49</sup> M. Schreyer,<sup>174</sup> C. Schroeder,<sup>83</sup>  
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Ph. Schwemling,<sup>136</sup> R. Schwienhorst,<sup>90</sup> J. Schwindling,<sup>136</sup> T. Schwindt,<sup>21</sup> F. G. Sciacca,<sup>17</sup> E. Scifo,<sup>117</sup> G. Sciolla,<sup>23</sup>  
F. Scuri,<sup>124a,124b</sup> F. Scutti,<sup>21</sup> J. Searcy,<sup>89</sup> G. Sedov,<sup>42</sup> E. Sedykh,<sup>123</sup> P. Seema,<sup>21</sup> S. C. Seidel,<sup>105</sup> A. Seiden,<sup>137</sup> F. Seifert,<sup>128</sup>  
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C. Serfon,<sup>30</sup> L. Serin,<sup>117</sup> L. Serkin,<sup>164a,164b</sup> T. Serre,<sup>85</sup> M. Sessa,<sup>134a,134b</sup> R. Seuster,<sup>159a</sup> H. Severini,<sup>113</sup> T. Sfiligoj,<sup>75</sup>  
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P. B. Shatalov,<sup>97</sup> K. Shaw,<sup>164a,164b</sup> S. M. Shaw,<sup>84</sup> A. Shcherbakova,<sup>146a,146b</sup> C. Y. Shehu,<sup>149</sup> P. Sherwood,<sup>78</sup> L. Shi,<sup>151,hh</sup>  
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S. Shojaii,<sup>91a,91b</sup> S. Shrestha,<sup>111</sup> E. Shulga,<sup>98</sup> M. A. Shupe,<sup>7</sup> S. Shushkevich,<sup>42</sup> P. Sicho,<sup>127</sup> P. E. Sidebo,<sup>147</sup>  
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T. B. Sjursen,<sup>14</sup> M. B. Skinner,<sup>72</sup> H. P. Skottowe,<sup>57</sup> P. Skubic,<sup>113</sup> M. Slater,<sup>18</sup> T. Slavicek,<sup>128</sup> M. Slawinska,<sup>107</sup>  
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O. Smirnova,<sup>81</sup> M. N. K. Smith,<sup>35</sup> R. W. Smith,<sup>35</sup> M. Smizanska,<sup>72</sup> K. Smolek,<sup>128</sup> A. A. Snesev,<sup>96</sup> G. Snidero,<sup>76</sup>  
S. Snyder,<sup>25</sup> R. Sobie,<sup>169,1</sup> F. Socher,<sup>44</sup> A. Soffer,<sup>153</sup> D. A. Soh,<sup>151,hh</sup> G. Sokhrannyi,<sup>75</sup> C. A. Solans,<sup>30</sup> M. Solar,<sup>128</sup>  
J. Solc,<sup>128</sup> E. Yu. Soldatov,<sup>98</sup> U. Soldevila,<sup>167</sup> A. A. Solodkov,<sup>130</sup> A. Soloshenko,<sup>65</sup> O. V. Solovyanov,<sup>130</sup> V. Solovyeve,<sup>123</sup>  
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M. Sosebee,<sup>8</sup> C. L. Sotiropoulou,<sup>124a,124b</sup> R. Soualah,<sup>164a,164c</sup> A. M. Soukharev,<sup>109,d</sup> D. South,<sup>42</sup> B. C. Sowden,<sup>77</sup>  
S. Spagnolo,<sup>73a,73b</sup> M. Spalla,<sup>124a,124b</sup> M. Spangenberg,<sup>170</sup> F. Spanò,<sup>77</sup> W. R. Spearman,<sup>57</sup> D. Sperlich,<sup>16</sup> F. Spettel,<sup>101</sup>  
R. Spighi,<sup>20a</sup> G. Spigo,<sup>30</sup> L. A. Spiller,<sup>88</sup> M. Spousta,<sup>129</sup> T. Spreitzer,<sup>158</sup> R. D. St. Denis,<sup>53,a</sup> A. Stabile,<sup>91a</sup> S. Staerz,<sup>44</sup>  
J. Stahlman,<sup>122</sup> R. Stamen,<sup>58a</sup> S. Stamm,<sup>16</sup> E. Stanecka,<sup>39</sup> C. Stanescu,<sup>134a</sup> M. Stanescu-Bellu,<sup>42</sup> M. M. Stanitzki,<sup>42</sup>  
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- B. Stelzer,<sup>142</sup> H. J. Stelzer,<sup>30</sup> O. Stelzer-Chilton,<sup>159a</sup> H. Stenzel,<sup>52</sup> G. A. Stewart,<sup>53</sup> J. A. Stillings,<sup>21</sup> M. C. Stockton,<sup>87</sup> M. Stoebe,<sup>87</sup> G. Stoicea,<sup>26b</sup> P. Stolte,<sup>54</sup> S. Stonjek,<sup>101</sup> A. R. Stradling,<sup>8</sup> A. Straessner,<sup>44</sup> M. E. Stramaglia,<sup>17</sup> J. Strandberg,<sup>147</sup> S. Strandberg,<sup>146a,146b</sup> A. Strandlie,<sup>119</sup> E. Strauss,<sup>143</sup> M. Strauss,<sup>113</sup> P. Strizenec,<sup>144b</sup> R. Ströhmer,<sup>174</sup> D. M. Strom,<sup>116</sup> R. Stroynowski,<sup>40</sup> A. Strubig,<sup>106</sup> S. A. Stucci,<sup>17</sup> B. Stugu,<sup>14</sup> N. A. Styles,<sup>42</sup> D. Su,<sup>143</sup> J. Su,<sup>125</sup> R. Subramaniam,<sup>79</sup> A. Succurro,<sup>12</sup> S. Suchek,<sup>58a</sup> Y. Sugaya,<sup>118</sup> M. Suk,<sup>128</sup> V. V. Sulin,<sup>96</sup> S. Sultansoy,<sup>4c</sup> T. Sumida,<sup>68</sup> S. 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Ticse Torres,<sup>85</sup> V. O. Tikhomirov,<sup>96,jj</sup> Yu. A. Tikhonov,<sup>109,d</sup> S. Timoshenko,<sup>98</sup> E. Tiouchichine,<sup>85</sup> P. Tipton,<sup>176</sup> S. Tisserant,<sup>85</sup> K. Todome,<sup>157</sup> T. Todorov,<sup>5,a</sup> S. Todorova-Nova,<sup>129</sup> J. Tojo,<sup>70</sup> S. Tokár,<sup>144a</sup> K. Tokushuku,<sup>66</sup> K. Tollefson,<sup>90</sup> E. Tolley,<sup>57</sup> L. Tomlinson,<sup>84</sup> M. Tomoto,<sup>103</sup> L. Tompkins,<sup>143,kk</sup> K. Toms,<sup>105</sup> E. Torrence,<sup>116</sup> H. Torres,<sup>142</sup> E. Torró Pastor,<sup>138</sup> J. Toth,<sup>85,ll</sup> F. Touchard,<sup>85</sup> D. R. Tovey,<sup>139</sup> T. Trefzger,<sup>174</sup> L. Tremblet,<sup>30</sup> A. Tricoli,<sup>30</sup> I. M. Trigger,<sup>159a</sup> S. Trincas-Duvoid,<sup>80</sup> M. F. Tripiana,<sup>12</sup> W. Trischuk,<sup>158</sup> B. Trocmé,<sup>55</sup> C. Troncon,<sup>91a</sup> M. Trottier-McDonald,<sup>15</sup> M. Trovatelli,<sup>169</sup> L. Truong,<sup>164a,164c</sup> M. Trzebinski,<sup>39</sup> A. Trzupek,<sup>39</sup> C. Tsarouchas,<sup>30</sup> J. C-L. Tseng,<sup>120</sup> P. V. Tsiareshka,<sup>92</sup> D. Tsionou,<sup>154</sup> G. Tsipolitis,<sup>10</sup> N. Tsirintanis,<sup>9</sup> S. Tsiskaridze,<sup>12</sup> V. Tsiskaridze,<sup>48</sup> E. G. Tskhadadze,<sup>51a</sup> I. I. Tsukerman,<sup>97</sup> V. Tsulaia,<sup>15</sup> S. Tsuno,<sup>66</sup> D. Tsybychev,<sup>148</sup> A. Tudorache,<sup>26b</sup> V. Tudorache,<sup>26b</sup> A. N. Tuna,<sup>57</sup> S. A. Tupputi,<sup>20a,20b</sup> S. Turchikhin,<sup>99,ii</sup> D. Turecek,<sup>128</sup> R. Turra,<sup>91a,91b</sup> A. J. Turvey,<sup>40</sup> P. M. Tuts,<sup>35</sup> A. Tykhonov,<sup>49</sup> M. Tylmad,<sup>146a,146b</sup> M. Tyndel,<sup>131</sup> I. Ueda,<sup>155</sup> R. Ueno,<sup>29</sup> M. Ughetto,<sup>146a,146b</sup> M. Ugland,<sup>14</sup> F. Ukegawa,<sup>160</sup> G. Unal,<sup>30</sup> A. Undrus,<sup>25</sup> G. Unel,<sup>163</sup> F. C. Ungaro,<sup>48</sup> Y. Unno,<sup>66</sup> C. Unverdorben,<sup>100</sup> J. Urban,<sup>144b</sup> P. Urquijo,<sup>88</sup> P. Urrejola,<sup>83</sup> G. Usai,<sup>8</sup> A. Usanova,<sup>62</sup> L. Vacavant,<sup>85</sup> V. Vacek,<sup>128</sup> B. Vachon,<sup>87</sup> C. Valderanis,<sup>83</sup> N. Valencic,<sup>107</sup> S. Valentinetti,<sup>20a,20b</sup> A. Valero,<sup>167</sup> L. Valery,<sup>12</sup> S. Valkar,<sup>129</sup> E. Valladolid Gallego,<sup>167</sup> S. Vallecorsa,<sup>49</sup> J. A. Valls Ferrer,<sup>167</sup> W. Van Den Wollenberg,<sup>107</sup> P. C. Van Der Deijl,<sup>107</sup> R. van der Geer,<sup>107</sup> H. van der Graaf,<sup>107</sup> N. van Eldik,<sup>152</sup> P. van Gemmeren,<sup>6</sup> J. Van Nieuwkoop,<sup>142</sup> I. van Vulpen,<sup>107</sup> M. C. van Woerden,<sup>30</sup> M. Vanadia,<sup>132a,132b</sup> W. Vandelli,<sup>30</sup> R. Vanguri,<sup>122</sup> A. Vaniachine,<sup>6</sup> F. Vannucci,<sup>80</sup> G. Vardanyan,<sup>177</sup> R. Vari,<sup>132a</sup> E. W. Varnes,<sup>7</sup> T. Varol,<sup>40</sup> D. Varouchas,<sup>80</sup> A. Vartapetian,<sup>8</sup> K. E. Varvell,<sup>150</sup> F. Vazeille,<sup>34</sup> T. Vazquez Schroeder,<sup>87</sup> J. Veatch,<sup>7</sup> L. M. Veloce,<sup>158</sup> F. Veloso,<sup>126a,126c</sup> T. Velz,<sup>21</sup> S. Veneziano,<sup>132a</sup> A. Ventura,<sup>73a,73b</sup> D. Ventura,<sup>86</sup> M. Venturi,<sup>169</sup> N. Venturi,<sup>158</sup> A. Venturini,<sup>23</sup> V. Vercesi,<sup>121a</sup> M. Verducci,<sup>132a,132b</sup> W. Verkerke,<sup>107</sup> J. C. Vermeulen,<sup>107</sup> A. Vest,<sup>44</sup> M. C. Vetterli,<sup>142,e</sup> O. Viazlo,<sup>81</sup> I. Vichou,<sup>165</sup> T. Vickey,<sup>139</sup> O. E. Vickey Boeriu,<sup>139</sup> G. H. A. Viehhauser,<sup>120</sup> S. Viel,<sup>15</sup> R. Vigne,<sup>62</sup> M. Villa,<sup>20a,20b</sup> M. Villaplana Perez,<sup>91a,91b</sup> E. Vilucchi,<sup>47</sup> M. G. Vincter,<sup>29</sup> V. B. Vinogradov,<sup>65</sup> I. Vivarelli,<sup>149</sup> F. Vives Vaque,<sup>3</sup> S. Vlachos,<sup>10</sup> D. Vladoiu,<sup>100</sup> M. Vlasak,<sup>128</sup> M. Vogel,<sup>32a</sup> P. Vokac,<sup>128</sup> G. Volpi,<sup>124a,124b</sup> M. Volpi,<sup>88</sup> H. von der Schmitt,<sup>101</sup> H. von Radziewski,<sup>48</sup> E. von Toerne,<sup>21</sup> V. Vorobel,<sup>129</sup> K. Vorobev,<sup>98</sup> M. Vos,<sup>167</sup> R. Voss,<sup>30</sup> J. H. Vosseveld,<sup>74</sup> N. Vranjes,<sup>13</sup> M. Vranjes Milosavljevic,<sup>13</sup> V. Vrba,<sup>127</sup> M. Vreeswijk,<sup>107</sup> R. Vuillermet,<sup>30</sup> I. Vukotic,<sup>31</sup> Z. Vykydal,<sup>128</sup> P. Wagner,<sup>21</sup> W. Wagner,<sup>175</sup> H. Wahlberg,<sup>71</sup> S. Wahrmund,<sup>44</sup> J. Wakabayashi,<sup>103</sup> J. Walder,<sup>72</sup> R. Walker,<sup>100</sup> W. Walkowiak,<sup>141</sup> C. Wang,<sup>151</sup> F. Wang,<sup>173</sup> H. Wang,<sup>15</sup> H. Wang,<sup>40</sup> J. Wang,<sup>42</sup> J. Wang,<sup>150</sup> K. Wang,<sup>87</sup> R. Wang,<sup>6</sup> S. M. Wang,<sup>151</sup> T. Wang,<sup>21</sup> T. Wang,<sup>35</sup> X. Wang,<sup>176</sup> C. Wanotayaroj,<sup>116</sup> A. Warburton,<sup>87</sup> C. P. Ward,<sup>28</sup> D. R. Wardrope,<sup>78</sup> A. Washbrook,<sup>46</sup> C. Wasicki,<sup>42</sup> P. M. Watkins,<sup>18</sup> A. T. Watson,<sup>18</sup> I. J. Watson,<sup>150</sup> M. F. Watson,<sup>18</sup> G. Watts,<sup>138</sup> S. Watts,<sup>84</sup> B. M. Waugh,<sup>78</sup> S. Webb,<sup>84</sup> M. S. Weber,<sup>17</sup> S. W. Weber,<sup>174</sup> J. S. Webster,<sup>31</sup> A. R. Weidberg,<sup>120</sup> B. Weinert,<sup>61</sup> J. Weingarten,<sup>54</sup> C. Weiser,<sup>48</sup> H. Weits,<sup>107</sup> P. S. Wells,<sup>30</sup> T. Wenaus,<sup>25</sup> T. Wengler,<sup>30</sup> S. Wenig,<sup>30</sup> N. Wermes,<sup>21</sup> M. Werner,<sup>48</sup> P. Werner,<sup>30</sup> M. Wessels,<sup>58a</sup> J. Wetter,<sup>161</sup> K. Whalen,<sup>116</sup> A. M. Wharton,<sup>72</sup> A. White,<sup>8</sup> M. J. White,<sup>1</sup> R. White,<sup>32b</sup> S. White,<sup>124a,124b</sup> D. Whiteson,<sup>163</sup> F. J. Wickens,<sup>131</sup> W. Wiedenmann,<sup>173</sup> M. WIELERS,<sup>131</sup> P. Wienemann,<sup>21</sup> C. Wigglesworth,<sup>36</sup> L. A. M. Wiik-Fuchs,<sup>21</sup> A. Wildauer,<sup>101</sup> H. G. Wilkens,<sup>30</sup> H. H. Williams,<sup>122</sup> S. Williams,<sup>107</sup> C. Willis,<sup>90</sup> S. Willocq,<sup>86</sup> A. Wilson,<sup>89</sup> J. A. Wilson,<sup>18</sup> I. Wingerter-Seez,<sup>5</sup> F. Winklmeier,<sup>116</sup> B. T. Winter,<sup>21</sup>

M. Wittgen,<sup>143</sup> J. Wittkowski,<sup>100</sup> S. J. Wollstadt,<sup>83</sup> M. W. Wolter,<sup>39</sup> H. Wolters,<sup>126a,126c</sup> B. K. Wosiek,<sup>39</sup> J. Wotschack,<sup>30</sup> M. J. Woudstra,<sup>84</sup> K. W. Wozniak,<sup>39</sup> M. Wu,<sup>55</sup> M. Wu,<sup>31</sup> S. L. Wu,<sup>173</sup> X. Wu,<sup>49</sup> Y. Wu,<sup>89</sup> T. R. Wyatt,<sup>84</sup> B. M. Wynne,<sup>46</sup> S. Xella,<sup>36</sup> D. Xu,<sup>33a</sup> L. Xu,<sup>25</sup> B. Yabsley,<sup>150</sup> S. Yacoob,<sup>145a</sup> R. Yakabe,<sup>67</sup> M. Yamada,<sup>66</sup> D. Yamaguchi,<sup>157</sup> Y. Yamaguchi,<sup>118</sup> A. Yamamoto,<sup>66</sup> S. Yamamoto,<sup>155</sup> T. Yamanaka,<sup>155</sup> K. Yamauchi,<sup>103</sup> Y. Yamazaki,<sup>67</sup> Z. Yan,<sup>22</sup> H. Yang,<sup>33e</sup> H. Yang,<sup>173</sup> Y. Yang,<sup>151</sup> W.-M. Yao,<sup>15</sup> Y. Yasu,<sup>66</sup> E. Yatsenko,<sup>5</sup> K. H. Yau Wong,<sup>21</sup> J. Ye,<sup>40</sup> S. Ye,<sup>25</sup> I. Yeletsikh,<sup>65</sup> A. L. Yen,<sup>57</sup> E. Yildirim,<sup>42</sup> K. Yorita,<sup>171</sup> R. Yoshida,<sup>6</sup> K. Yoshihara,<sup>122</sup> C. Young,<sup>143</sup> C. J. S. Young,<sup>30</sup> S. Youssef,<sup>22</sup> D. R. Yu,<sup>15</sup> J. Yu,<sup>8</sup> J. M. Yu,<sup>89</sup> J. Yu,<sup>114</sup> L. Yuan,<sup>67</sup> S. P. Y. Yuen,<sup>21</sup> A. Yurkewicz,<sup>108</sup> I. Yusuff,<sup>28,mm</sup> B. Zabinski,<sup>39</sup> R. Zaidan,<sup>63</sup> A. M. Zaitsev,<sup>130,dd</sup> J. Zalieckas,<sup>14</sup> A. Zaman,<sup>148</sup> S. Zambito,<sup>57</sup> L. Zanello,<sup>132a,132b</sup> D. Zanzi,<sup>88</sup> C. Zeitnitz,<sup>175</sup> M. Zeman,<sup>128</sup> A. Zemla,<sup>38a</sup> Q. Zeng,<sup>143</sup> K. Zengel,<sup>23</sup> O. Zenin,<sup>130</sup> T. Ženiš,<sup>144a</sup> D. Zerwas,<sup>117</sup> D. Zhang,<sup>89</sup> F. Zhang,<sup>173</sup> H. Zhang,<sup>33c</sup> J. Zhang,<sup>6</sup> L. Zhang,<sup>48</sup> R. Zhang,<sup>33b,j</sup> X. Zhang,<sup>33d</sup> Z. Zhang,<sup>117</sup> X. Zhao,<sup>40</sup> Y. Zhao,<sup>33d,117</sup> Z. Zhao,<sup>33b</sup> A. Zhemchugov,<sup>65</sup> J. Zhong,<sup>120</sup> B. Zhou,<sup>89</sup> C. Zhou,<sup>45</sup> L. Zhou,<sup>35</sup> L. Zhou,<sup>40</sup> M. Zhou,<sup>148</sup> N. Zhou,<sup>33f</sup> C. G. Zhu,<sup>33d</sup> H. Zhu,<sup>33a</sup> J. Zhu,<sup>89</sup> Y. Zhu,<sup>33b</sup> X. Zhuang,<sup>33a</sup> K. Zhukov,<sup>96</sup> A. Zibell,<sup>174</sup> D. Zieminska,<sup>61</sup> N. I. Zimine,<sup>65</sup> C. Zimmermann,<sup>83</sup> S. Zimmermann,<sup>48</sup> Z. Zinonos,<sup>54</sup> M. Zinser,<sup>83</sup> M. Ziolkowski,<sup>141</sup> L. Živković,<sup>13</sup> G. Zobernig,<sup>173</sup> A. Zoccoli,<sup>20a,20b</sup> M. zur Nedden,<sup>16</sup> G. Zurzolo,<sup>104a,104b</sup> and L. Zwalinski<sup>30</sup>

(ATLAS Collaboration)

<sup>1</sup>*Department of Physics, University of Adelaide, Adelaide, Australia*

<sup>2</sup>*Physics Department, SUNY Albany, Albany, New York, USA*

<sup>3</sup>*Department of Physics, University of Alberta, Edmonton AB, Canada*

<sup>4a</sup>*Department of Physics, Ankara University, Ankara, Turkey*

<sup>4b</sup>*Istanbul Aydin University, Istanbul, Turkey*

<sup>4c</sup>*Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey*

<sup>5</sup>*LAPP, CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux, France*

<sup>6</sup>*High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA*

<sup>7</sup>*Department of Physics, University of Arizona, Tucson, Arizona, USA*

<sup>8</sup>*Department of Physics, The University of Texas at Arlington, Arlington, Texas, USA*

<sup>9</sup>*Physics Department, University of Athens, Athens, Greece*

<sup>10</sup>*Physics Department, National Technical University of Athens, Zografou, Greece*

<sup>11</sup>*Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan*

<sup>12</sup>*Institut de Física d'Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain*

<sup>13</sup>*Institute of Physics, University of Belgrade, Belgrade, Serbia*

<sup>14</sup>*Department for Physics and Technology, University of Bergen, Bergen, Norway*

<sup>15</sup>*Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA*

<sup>16</sup>*Department of Physics, Humboldt University, Berlin, Germany*

<sup>17</sup>*Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland*

<sup>18</sup>*School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom*

<sup>19a</sup>*Department of Physics, Bogazici University, Istanbul, Turkey*

<sup>19b</sup>*Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey*

<sup>19c</sup>*Department of Physics, Dogus University, Istanbul, Turkey*

<sup>20a</sup>*INFN Sezione di Bologna, Bologna, Italy*

<sup>20b</sup>*Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy*

<sup>21</sup>*Physikalisches Institut, University of Bonn, Bonn, Germany*

<sup>22</sup>*Department of Physics, Boston University, Boston, Massachusetts, USA*

<sup>23</sup>*Department of Physics, Brandeis University, Waltham, Massachusetts, USA*

<sup>24a</sup>*Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil*

<sup>24b</sup>*Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil*

<sup>24c</sup>*Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil*

<sup>24d</sup>*Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil*

<sup>25</sup>*Physics Department, Brookhaven National Laboratory, Upton, New York, USA*

<sup>26a</sup>*Transilvania University of Brasov, Brasov, Romania*

<sup>26b</sup>*National Institute of Physics and Nuclear Engineering, Bucharest, Romania*

<sup>26c</sup>*National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca, Romania*

- <sup>26d</sup>University Politehnica Bucharest, Bucharest, Romania  
<sup>26e</sup>West University in Timisoara, Timisoara, Romania  
<sup>27</sup>Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina  
<sup>28</sup>Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom  
<sup>29</sup>Department of Physics, Carleton University, Ottawa ON, Canada  
<sup>30</sup>CERN, Geneva, Switzerland  
<sup>31</sup>Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA  
<sup>32a</sup>Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile  
<sup>32b</sup>Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile  
<sup>33a</sup>Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China  
<sup>33b</sup>Department of Modern Physics, University of Science and Technology of China, Anhui, China  
<sup>33c</sup>Department of Physics, Nanjing University, Jiangsu, China  
<sup>33d</sup>School of Physics, Shandong University, Shandong, China  
<sup>33e</sup>Department of Physics and Astronomy, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai, China  
<sup>33f</sup>Physics Department, Tsinghua University, Beijing 100084, China  
<sup>34</sup>Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France  
<sup>35</sup>Nevis Laboratory, Columbia University, Irvington, New York, USA  
<sup>36</sup>Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark  
<sup>37a</sup>INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Frascati, Italy  
<sup>37b</sup>Dipartimento di Fisica, Università della Calabria, Rende, Italy  
<sup>38a</sup>AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland  
<sup>38b</sup>Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland  
<sup>39</sup>Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland  
<sup>40</sup>Physics Department, Southern Methodist University, Dallas, Texas, USA  
<sup>41</sup>Physics Department, University of Texas at Dallas, Richardson, Texas, USA  
<sup>42</sup>DESY, Hamburg and Zeuthen, Germany  
<sup>43</sup>Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany  
<sup>44</sup>Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany  
<sup>45</sup>Department of Physics, Duke University, Durham, North Carolina, USA  
<sup>46</sup>SUPA—School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom  
<sup>47</sup>INFN Laboratori Nazionali di Frascati, Frascati, Italy  
<sup>48</sup>Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany  
<sup>49</sup>Section de Physique, Université de Genève, Geneva, Switzerland  
<sup>50a</sup>INFN Sezione di Genova, Genova, Italy  
<sup>50b</sup>Dipartimento di Fisica, Università di Genova, Genova, Italy  
<sup>51a</sup>E. Andronikashvili Institute of Physics, Iv. Javakishvili Tbilisi State University, Tbilisi, Georgia  
<sup>51b</sup>High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia  
<sup>52</sup>II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany  
<sup>53</sup>SUPA—School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom  
<sup>54</sup>II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany  
<sup>55</sup>Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France  
<sup>56</sup>Department of Physics, Hampton University, Hampton, Virginia, USA  
<sup>57</sup>Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA  
<sup>58a</sup>Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany  
<sup>58b</sup>Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany  
<sup>58c</sup>ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany  
<sup>59</sup>Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan  
<sup>60a</sup>Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China  
<sup>60b</sup>Department of Physics, The University of Hong Kong, Hong Kong, China  
<sup>60c</sup>Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China  
<sup>61</sup>Department of Physics, Indiana University, Bloomington, Indiana, USA  
<sup>62</sup>Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria  
<sup>63</sup>University of Iowa, Iowa City, Iowa, USA  
<sup>64</sup>Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA  
<sup>65</sup>Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia



- <sup>66</sup>KEK, High Energy Accelerator Research Organization, Tsukuba, Japan  
<sup>67</sup>Graduate School of Science, Kobe University, Kobe, Japan  
<sup>68</sup>Faculty of Science, Kyoto University, Kyoto, Japan  
<sup>69</sup>Kyoto University of Education, Kyoto, Japan  
<sup>70</sup>Department of Physics, Kyushu University, Fukuoka, Japan  
<sup>71</sup>Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina  
<sup>72</sup>Physics Department, Lancaster University, Lancaster, United Kingdom  
<sup>73a</sup>INFN Sezione di Lecce, Lecce, Italy  
<sup>73b</sup>Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy  
<sup>74</sup>Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom  
<sup>75</sup>Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia  
<sup>76</sup>School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom  
<sup>77</sup>Department of Physics, Royal Holloway University of London, Surrey, United Kingdom  
<sup>78</sup>Department of Physics and Astronomy, University College London, London, United Kingdom  
<sup>79</sup>Louisiana Tech University, Ruston, Louisiana, USA  
<sup>80</sup>Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France  
<sup>81</sup>Fysiska institutionen, Lunds universitet, Lund, Sweden  
<sup>82</sup>Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain  
<sup>83</sup>Institut für Physik, Universität Mainz, Mainz, Germany  
<sup>84</sup>School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom  
<sup>85</sup>CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France  
<sup>86</sup>Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA  
<sup>87</sup>Department of Physics, McGill University, Montreal QC, Canada  
<sup>88</sup>School of Physics, University of Melbourne, Victoria, Australia  
<sup>89</sup>Department of Physics, The University of Michigan, Ann Arbor, Michigan, USA  
<sup>90</sup>Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA  
<sup>91a</sup>INFN Sezione di Milano, Milano, Italy  
<sup>91b</sup>Dipartimento di Fisica, Università di Milano, Milano, Italy  
<sup>92</sup>B. I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus  
<sup>93</sup>National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus  
<sup>94</sup>Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA  
<sup>95</sup>Group of Particle Physics, University of Montreal, Montreal QC, Canada  
<sup>96</sup>P. N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia  
<sup>97</sup>Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia  
<sup>98</sup>National Research Nuclear University MEPhI, Moscow, Russia  
<sup>99</sup>D. V. Skobeltsyn Institute of Nuclear Physics, M. V. Lomonosov Moscow State University, Moscow, Russia  
<sup>100</sup>Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany  
<sup>101</sup>Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany  
<sup>102</sup>Nagasaki Institute of Applied Science, Nagasaki, Japan  
<sup>103</sup>Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan  
<sup>104a</sup>INFN Sezione di Napoli, Napoli, Italy  
<sup>104b</sup>Dipartimento di Fisica, Università di Napoli, Napoli, Italy  
<sup>105</sup>Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA  
<sup>106</sup>Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands  
<sup>107</sup>Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands  
<sup>108</sup>Department of Physics, Northern Illinois University, DeKalb, Illinois, USA  
<sup>109</sup>Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia  
<sup>110</sup>Department of Physics, New York University, New York, New York, USA  
<sup>111</sup>Ohio State University, Columbus, Ohio, USA  
<sup>112</sup>Faculty of Science, Okayama University, Okayama, Japan  
<sup>113</sup>Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA  
<sup>114</sup>Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA  
<sup>115</sup>Palacký University, RCPTM, Olomouc, Czech Republic  
<sup>116</sup>Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA  
<sup>117</sup>LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France



- <sup>118</sup>*Graduate School of Science, Osaka University, Osaka, Japan*
- <sup>119</sup>*Department of Physics, University of Oslo, Oslo, Norway*
- <sup>120</sup>*Department of Physics, Oxford University, Oxford, United Kingdom*
- <sup>121a</sup>*INFN Sezione di Pavia, Pavia, Italy*
- <sup>121b</sup>*Dipartimento di Fisica, Università di Pavia, Pavia, Italy*
- <sup>122</sup>*Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA*
- <sup>123</sup>*National Research Centre “Kurchatov Institute” B.P.Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia*
- <sup>124a</sup>*INFN Sezione di Pisa, Pisa, Italy*
- <sup>124b</sup>*Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy*
- <sup>125</sup>*Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA*
- <sup>126a</sup>*Laboratório de Instrumentação e Física Experimental de Partículas—LIP, Lisboa, Portugal*
- <sup>126b</sup>*Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal*
- <sup>126c</sup>*Department of Physics, University of Coimbra, Coimbra, Portugal*
- <sup>126d</sup>*Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal*
- <sup>126e</sup>*Departamento de Física, Universidade do Minho, Braga, Portugal*
- <sup>126f</sup>*Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain*
- <sup>126g</sup>*Dep Física and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal*
- <sup>127</sup>*Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic*
- <sup>128</sup>*Czech Technical University in Prague, Praha, Czech Republic*
- <sup>129</sup>*Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic*
- <sup>130</sup>*State Research Center Institute for High Energy Physics (Protvino), NRC KI, Russia*
- <sup>131</sup>*Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom*
- <sup>132a</sup>*INFN Sezione di Roma, Roma, Italy*
- <sup>132b</sup>*Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy*
- <sup>133a</sup>*INFN Sezione di Roma Tor Vergata, Roma, Italy*
- <sup>133b</sup>*Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy*
- <sup>134a</sup>*INFN Sezione di Roma Tre, Roma, Italy*
- <sup>134b</sup>*Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy*
- <sup>135a</sup>*Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies—Université Hassan II, Casablanca, Morocco*
- <sup>135b</sup>*Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat, Morocco*
- <sup>135c</sup>*Faculté des Sciences Smlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco*
- <sup>135d</sup>*Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco*
- <sup>135e</sup>*Faculté des sciences, Université Mohammed V, Rabat, Morocco*
- <sup>136</sup>*DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat à l’Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France*
- <sup>137</sup>*Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA*
- <sup>138</sup>*Department of Physics, University of Washington, Seattle, Washington, USA*
- <sup>139</sup>*Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom*
- <sup>140</sup>*Department of Physics, Shinshu University, Nagano, Japan*
- <sup>141</sup>*Fachbereich Physik, Universität Siegen, Siegen, Germany*
- <sup>142</sup>*Department of Physics, Simon Fraser University, Burnaby BC, Canada*
- <sup>143</sup>*SLAC National Accelerator Laboratory, Stanford, California, USA*
- <sup>144a</sup>*Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava, Slovak Republic*
- <sup>144b</sup>*Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic*
- <sup>145a</sup>*Department of Physics, University of Cape Town, Cape Town, South Africa*
- <sup>145b</sup>*Department of Physics, University of Johannesburg, Johannesburg, South Africa*
- <sup>145c</sup>*School of Physics, University of the Witwatersrand, Johannesburg, South Africa*
- <sup>146a</sup>*Department of Physics, Stockholm University, Sweden*
- <sup>146b</sup>*The Oskar Klein Centre, Stockholm, Sweden*
- <sup>147</sup>*Physics Department, Royal Institute of Technology, Stockholm, Sweden*
- <sup>148</sup>*Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, New York, USA*
- <sup>149</sup>*Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom*

- <sup>150</sup>*School of Physics, University of Sydney, Sydney, Australia*  
<sup>151</sup>*Institute of Physics, Academia Sinica, Taipei, Taiwan*  
<sup>152</sup>*Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel*  
<sup>153</sup>*Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel*  
<sup>154</sup>*Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece*  
<sup>155</sup>*International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan*  
<sup>156</sup>*Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan*  
<sup>157</sup>*Department of Physics, Tokyo Institute of Technology, Tokyo, Japan*  
<sup>158</sup>*Department of Physics, University of Toronto, Toronto ON, Canada*  
<sup>159a</sup>*TRIUMF, Vancouver BC, Canada*  
<sup>159b</sup>*Department of Physics and Astronomy, York University, Toronto ON, Canada*  
<sup>160</sup>*Faculty of Pure and Applied Sciences, and Center for Integrated Research in Fundamental Science and Engineering, University of Tsukuba, Tsukuba, Japan*  
<sup>161</sup>*Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA*  
<sup>162</sup>*Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia*  
<sup>163</sup>*Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA*  
<sup>164a</sup>*INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy*  
<sup>164b</sup>*ICTP, Trieste, Italy*  
<sup>164c</sup>*Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy*  
<sup>165</sup>*Department of Physics, University of Illinois, Urbana, Illinois, USA*  
<sup>166</sup>*Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden*  
<sup>167</sup>*Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain*  
<sup>168</sup>*Department of Physics, University of British Columbia, Vancouver BC, Canada*  
<sup>169</sup>*Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada*  
<sup>170</sup>*Department of Physics, University of Warwick, Coventry, United Kingdom*  
<sup>171</sup>*Waseda University, Tokyo, Japan*  
<sup>172</sup>*Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel*  
<sup>173</sup>*Department of Physics, University of Wisconsin, Madison, Wisconsin, USA*  
<sup>174</sup>*Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany*  
<sup>175</sup>*Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany*  
<sup>176</sup>*Department of Physics, Yale University, New Haven, Connecticut, USA*  
<sup>177</sup>*Yerevan Physics Institute, Yerevan, Armenia*  
<sup>178</sup>*Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France*

<sup>a</sup>Deceased.

<sup>b</sup>Also at Department of Physics, King's College London, London, United Kingdom.

<sup>c</sup>Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.

<sup>d</sup>Also at Novosibirsk State University, Novosibirsk, Russia.

<sup>e</sup>Also at TRIUMF, Vancouver BC, Canada.

<sup>f</sup>Also at Department of Physics, California State University, Fresno, California, USA.

<sup>g</sup>Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.

<sup>h</sup>Also at Departamento de Física e Astronomia, Faculdade de Ciências, Universidade do Porto, Portugal.

<sup>i</sup>Also at Tomsk State University, Tomsk, Russia.

<sup>j</sup>Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.

<sup>k</sup>Also at Università di Napoli Parthenope, Napoli, Italy.

<sup>l</sup>Also at Institute of Particle Physics (IPP), Canada.

<sup>m</sup>Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.

<sup>n</sup>Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.

<sup>o</sup>Also at Louisiana Tech University, Ruston, Louisiana, USA.

<sup>p</sup>Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.

<sup>q</sup>Also at Department of Physics, The University of Michigan, Ann Arbor, Michigan, USA.

<sup>r</sup>Also at Graduate School of Science, Osaka University, Osaka, Japan.

<sup>s</sup>Also at Department of Physics, National Tsing Hua University, Taiwan.

<sup>t</sup>Also at Department of Physics, The University of Texas at Austin, Austin, Texas, USA.

<sup>u</sup>Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.

<sup>v</sup>Also at CERN, Geneva, Switzerland.

- <sup>w</sup>Also at Georgian Technical University (GTU), Tbilisi, Georgia.
- <sup>x</sup>Also at Manhattan College, New York, New York, USA.
- <sup>y</sup>Also at Hellenic Open University, Patras, Greece.
- <sup>z</sup>Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
- <sup>aa</sup>Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France.
- <sup>bb</sup>Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
- <sup>cc</sup>Also at School of Physics, Shandong University, Shandong, China.
- <sup>dd</sup>Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
- <sup>ee</sup>Also at Section de Physique, Université de Genève, Geneva, Switzerland.
- <sup>ff</sup>Also at International School for Advanced Studies (SISSA), Trieste, Italy.
- <sup>gg</sup>Also at Department of Physics and Astronomy, University of South Carolina, Columbia, South Carolina, USA.
- <sup>hh</sup>Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.
- <sup>ii</sup>Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia.
- <sup>jj</sup>Also at National Research Nuclear University MEPhI, Moscow, Russia.
- <sup>kk</sup>Also at Department of Physics, Stanford University, Stanford, California, USA.
- <sup>ll</sup>Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
- <sup>mm</sup>Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.